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PRELIMINARY ECONOMIC EVALUATION OF THE
USE OF GRAPHITE COMPOSITE MATERIALS
IN SURFACE TRANSPORTATION

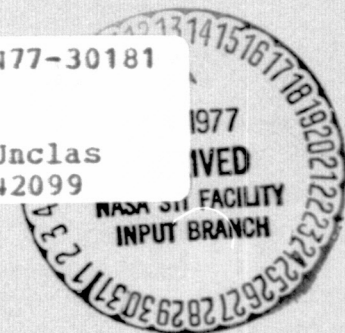
PHASE I RESULTS

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PRELIMINARY ECONOMIC EVALUATION OF THE
USE OF GRAPHITE COMPOSITE MATERIALS
IN SURFACE TRANSPORTATION

FINAL

PHASE I RESULTS

Contract NASW-2781

July 11, 1977

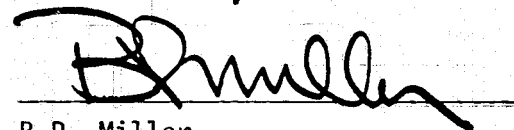
ECONOMICS OPERATIONS RESEARCH SYSTEMS ANALYSIS POLICY STUDIES TECHNOLOGY ASSESSMENT

NOTE OF TRANSMITTAL

This study of the potential technical and economic impacts of the use of graphite composite materials in surface transportation was performed for the National Aeronautics and Space Administration, under Contract NASW-2781, during May and June of 1977. Mr. Robert Rollins, at NASA Headquarters, served as the principal interface person between the ECON study team and various sources of information within NASA. Mr. George C. Deutsch, Mr. Gerald G. Kayten, and Dr. Michael J. Salkind all assisted in the formulation of the study, and directed the study team to many sources of technical information.

The ECON team for this study consisted of Mr. Keith Lietzke, Mr. B.P. Miller, Dr. Z.D. Nikodem, Mr. Peter Stevenson and Dr. Larry M. Sweet. The analysis of the composite materials industry was performed by Dr. Z.D. Nikodem. The use of graphite composites in surface transportation vehicles (particularly automobiles) was examined by Dr. L. Sweet. Mr. Keith Lietzke studied the economic incentives for the use of composites in the automobile industry and Mr. Peter Stevenson examined the national economic impacts. Mr. B.P. Miller was the study manager.

The reader of this report should note that the brief duration of this study presented constraints on the availability of information and the level of analysis performed. As a result of these constraints, the preliminary findings reported should be viewed as indications of possible trends that could result from the use of graphite composites in surface transportation. Additional study and analysis is required to provide answers that can be used with a greater degree of confidence.

A handwritten signature in dark ink, appearing to read 'B.P. Miller', is written over a horizontal line.

B.P. Miller
Vice President
Technology Assessment

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INTRODUCTION AND OVERVIEW

INTRODUCTION

NASA has developed and sponsored the use of high strength-to-weight graphite composite materials for aeronautical and space applications. In comparison to aluminum, iron and steel the graphite composites offer improved strength, stiffness, fatigue and corrosion resistance, and damping characteristics at reduced weight. During recent years graphite composites have been used in luxury sporting goods such as bicycles, golf clubs, and tennis rackets.

The OPEC oil embargo in 1973 and subsequent congressional legislation mandating improved automobile fuel efficiency have produced a strong interest on the part of the automotive industry in the use of aluminum, plastics and composite materials as substitutes for ferrous metals. Truck and railroad freight car manufacturers are also interested in use of plastics and composite materials; however, in this case the objective is to reduce the empty weight of the vehicle, thus increasing the load carrying capacity.

This report describes the results of the first phase of a proposed two-phase study of the possible applications of graphite composite materials in surface transportation vehicles, and the potential economic impacts of the use of graphite composite materials in these vehicles. Phase I was performed during May and June 1977. It should be noted at the outset that the reported results are based upon a two-month effort, and are intended to provide the basis for a more detailed study of the economic and social impacts of the use of graphite composite materials in surface transportation. Because of particular sensitivities concerning the interface between NASA and the U.S. automotive industry, the ECON study team was constrained by NASA not to contact the U.S. automotive industry during the course of this work. The brief duration of this phase of the study made the process of data collection and assimilation difficult. For example, the availability of testimony given by General Motors to National Highway Traffic Safety Administration (NHTSA) on their plans to achieve mandated 1985 fuel efficiency standards by redesign and material substitution was identified during June 1977. The testimony was requested from NHTSA, but had not been received at the time of the writing of this report. The absence of direct contact with the U.S. automotive industry during the Phase I study also removed the possibility of verifying with industry sources the materials substitution concepts which form the basis for the economic impacts described in this report. In light of these constraints, the preliminary findings described in this report should be viewed as trends in materials usage and possible economic impacts. Additional study and analysis is required to provide estimates of economic impact that can be used with a greater degree of confidence.

INTRODUCTION (CONTINUED)

This report consists of five major sections. The first section is an introduction and overview of the results of this Phase I study. This is followed by a discussion of composite materials, with emphasis on the identification of the characteristics of those materials that make them attractive for use in surface transportation. The third section describes the potential uses of graphite composites in surface transportation with emphasis on automotive applications and the effects of materials substitution on vehicle characteristics and performance. The fourth section provides preliminary estimates of the economic effects of the use of graphite composite materials on vehicle manufacturers and consumers. A preliminary estimate of the combined impact of vehicle design changes to meet mandated fuel efficiency requirements and the extensive use of graphite composite materials in the automotive industry on the national economy is contained in the final section of the report.

OBJECTIVE

The objective of this study (Phase I and II) is to provide a preliminary economic evaluation of the use of graphite composite materials in surface transportation vehicles in the United States.

Specific objectives of this Phase I study are to:

1. Identify the important potential uses of graphite composites in surface transportation in order to provide the basis for the selection of the important applications for further study at a later date.
2. Obtain preliminary estimates of the degree of substitution of graphite composites for presently used materials as a function of time.
3. Provide rough order of magnitude estimates of the economic impacts of the use of graphite composite materials in order to provide a preliminary identification of significant economic impacts.

On the basis of the findings of the Phase I study, it is proposed that specific areas of use of graphite composites in surface transportation be selected for a more detailed quantitative evaluation of economic and social impacts in Phase II.

OBJECTIVE

WHAT ARE THE ECONOMIC AND SOCIAL IMPACTS OF THE USE OF
GRAPHITE COMPOSITE MATERIALS IN U.S. SURFACE TRANSPORTATION
SYSTEMS?

SCOPE OF STUDY

This study develops preliminary estimates of the economic (and social) impacts of the use of graphite-bearing composite materials in U.S. surface transportation vehicles. For the purpose of this study the term surface transportation vehicle is defined as vehicles that are primarily intended to operate on roads or rails. Types of surface transportation vehicles considered include busses, passenger automobiles, streetcars, subway cars, trailers, trucks, and freight and passenger trains. It should be noted that ships, barges and freight containers may be important applications but have been excluded from this study.

The basis for the preliminary economic estimates described in this report is an assessment of the substitutability of graphite composites for aluminum, steel and other metals. In Phase II, factors such as life-cycle costs (cost of manufacture, cost of operation, cost of maintenance), safety, comfort or reliability, and consumer acceptance will be considered in the evaluation of the economic impact of substituting graphite composites for metals. Secondary effects of the use of graphite, such as the impacts on raw materials and finished parts suppliers, the vehicle maintenance infrastructure, and the recyclability of scrapped vehicles, will also be considered in Phase II.

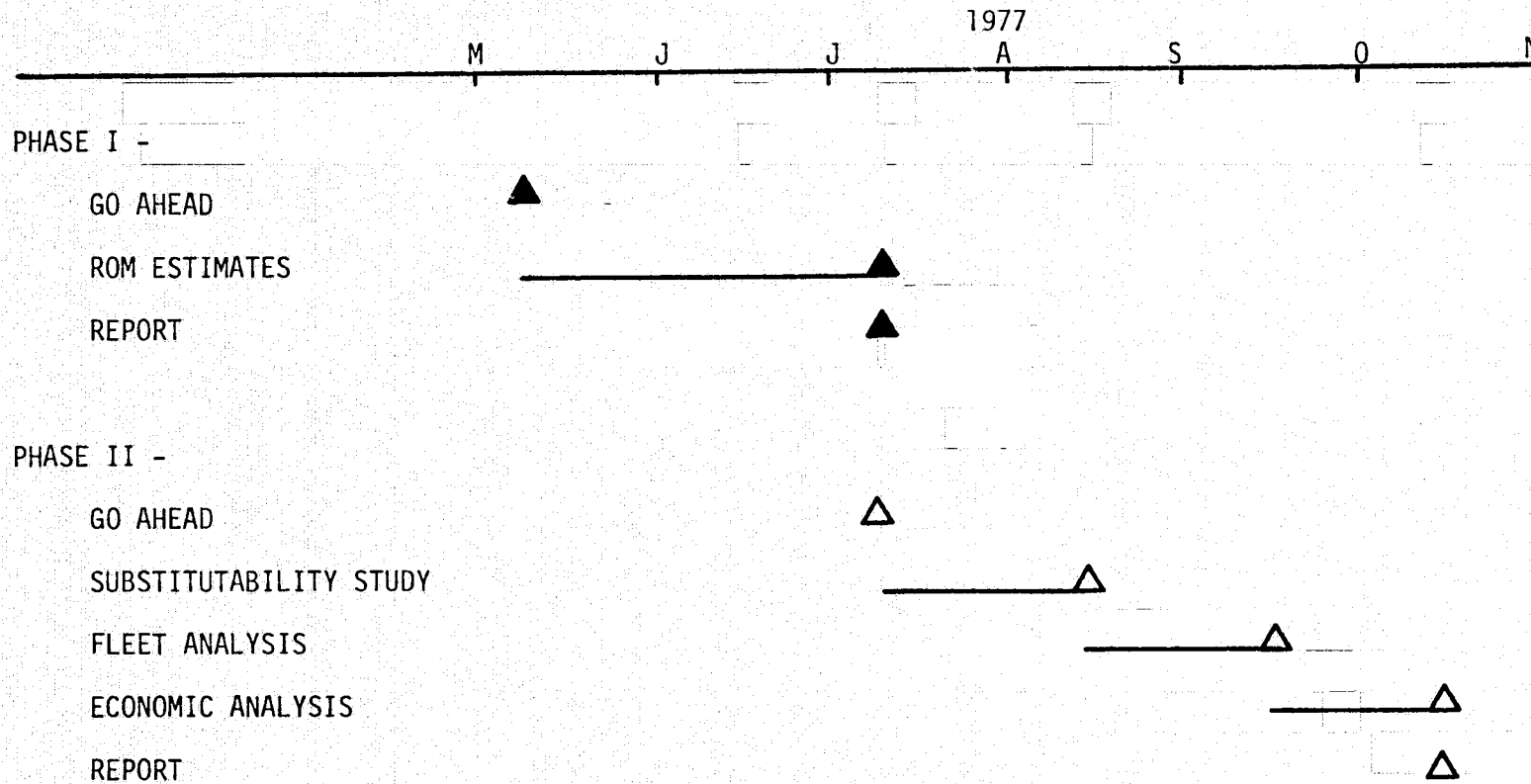
SCOPE OF STUDY

- GRAPHITE COMPOSITE MATERIALS
- SURFACE TRANSPORTATION VEHICLES
 - + PASSENGER AUTOMOBILES
 - + TRUCKS
 - + FREIGHT AND PASSENGER TRAINS
 - + BUSES
 - + SUBWAY CARS AND STREETCARS
- THE EFFECTS OF GRAPHITE COMPOSITE MATERIALS USE ON:
 - + THE NATIONAL ECONOMY
 - + OWNERS AND OPERATORS
 - + MANUFACTURERS
 - + ENERGY USAGE
 - + SAFETY
- SECONDARY EFFECTS

SCHEDULE

The schedule for this study is shown on the opposite page. The Phase I effort began during May 1977 and is completed with the submission of this report. The proposed Phase II study will begin during July 1977 and will be completed with the submission of a Final Report during November 1977.

SCHEDULE



▲ completed
 △ to be done

SUMMARY OF FINDINGS

The results of this Phase I study indicate that the major U.S. passenger car manufacturers are currently experimenting with the use of graphite composite components. While it is likely that graphite composite components will be introduced in production passenger cars by the 1985 model year, it appears that manufacturers are presently striving to meet the 1985 fuel efficiency requirements by downsizing, advances in engine technology and by the substitution of plastics and aluminum for iron and steel. It is believed that the maximum substitution of nonstructural plastics for metals will be achieved by 1985, and that further weight reductions after that date will require the increased use of aluminum and high strength-to-weight composite materials. The impetus for the extensive use of graphite composites in passenger cars appears to be in anticipation of the possibility of more stringent fuel efficiency requirements after 1985, and an emerging understanding that the extensive use of graphite composites could lead to a lightweight, fuel-efficient intermediate-sized car. It is estimated that the passenger car industry could consume about 860×10^6 pounds per year of graphite fiber for use in composite parts by 1990. This implies a significant expansion of the graphite fiber industry when compared to the present production for all purposes of about 250×10^3 pounds per year. Earlier extensive use of graphite composites in passenger cars appears to be inhibited by the present lack of a design data base, insufficient trained design personnel, production lead times and capital plant investment. The extensive use of plastics and graphite composites in passenger cars could accelerate the annual growth rate of the plastics sector of the economy from approximately 0.2 percent to 0.8 percent per year. A major increase in the growth of the nonferrous (aluminum) sector can also be anticipated. On the other hand, steel production in the most recent year of measurement (1975) was less than ten years ago, and the long-term growth rate of the steel industry in the United States is estimated to be nearly zero. Steel has not been a healthy industry in recent years and the substitution of aluminum, plastics and composite materials for ferrous metals in the passenger car industry will not improve this situation.

The results of this preliminary study also indicate that there is a potential market for graphite composites in trucks and railroad freight cars. The truck industry is essentially a derivative of the passenger car industry and good technology transfer between the two industries can be anticipated. A specific estimate of the size of the market for composite fibers in the truck manufacturing industry has not been made in Phase I; however, the truck manufacturing industry is second only to the passenger car industry in the consumption of materials and should represent a large market for graphite composites. The size of the railroad freight car market is estimated to be about a factor of 100 smaller than the size of the market for graphite composites in passenger cars. Other surface transportation applications in busses and light rail vehicles could also be achieved in the same time period; however, the size of the potential market in these applications is smaller than the other applications that have been identified.

SUMMARY OF FINDINGS - PHASE I

- WEIGHT OF AVERAGE U.S. PASSENGER CAR COULD DECREASE FROM APPROXIMATELY 4,000 POUNDS (1977) TO APPROXIMATELY 3,000 POUNDS (1985) AND APPROXIMATELY 2,400 POUNDS (1990).
 - + ENERGY CONSERVATION IS THE IMPETUS FOR WEIGHT REDUCTION
 - + 1985 FUEL EFFICIENCY GOAL CAN PROBABLY BE MET WITHOUT EXTENSIVE USE OF COMPOSITES
 - + WEIGHT REDUCTION WILL BE ACCOMPLISHED BY SIZE REDUCTION AND SUBSTITUTION OF ALUMINUM, PLASTICS AND COMPOSITES FOR IRON AND STEEL
 - + COMPOSITES WILL NOT BE USED IN PRODUCTION PASSENGER CARS BEFORE 1985, AND EXTENSIVE USE WILL NOT BE ACHIEVED BEFORE 1990
 - + FACTORS THAT INHIBIT EARLIER USE OF COMPOSITES INCLUDE LACK OF A DESIGN DATA BASE, INSUFFICIENT TECHNICAL PERSONNEL TRAINED IN APPLICATION OF COMPOSITES, CAPITAL PLANT INVESTMENT AND PRODUCTION LEAD TIMES
 - + RATE OF GROWTH OF SEVERAL SECTORS OF THE ECONOMY COULD BE AFFECTED BY THE SWITCH TO ALUMINUM, PLASTICS AND GRAPHITE COMPOSITE MATERIALS
 - + CONSUMPTION OF GRAPHITE FIBERS BY PASSENGER CAR INDUSTRY COULD REACH APPROXIMATELY 860×10^6 POUNDS PER YEAR BY 1990
 - + EXTENSIVE USE OF GRAPHITE COMPOSITES IN 1990 OPENS THE POSSIBILITY OF INTERMEDIATE-SIZED CARS ACHIEVING 32 TO 37 MILES PER GALLON, OR MEETING 1985 EPA REQUIREMENTS WHILE PRODUCING FULL-SIZED CARS.

SUMMARY OF FINDINGS - PHASE I (CONTINUED)

- EXTENSIVE USE OF GRAPHITE COMPOSITES IN TRUCKS AND RAILROAD FREIGHT CARS IS POSSIBLE BY 1985-90.
 - + GOAL IS EMPTY VEHICLE WEIGHT REDUCTION TO INCREASE MAXIMUM USEFUL LOAD CARRIED
 - + APPLICATION IN RAILROAD FREIGHT CAR MANUFACTURING IS INHIBITED BY THE DIFFUSE NATURE OF INDUSTRY, LACK OF RESEARCH AND DEVELOPMENT, AND HIGHER STRESS LEVELS THAN AUTOMOTIVE APPLICATIONS
 - + CONSUMPTION OF GRAPHITE FIBERS IN FREIGHT CAR MANUFACTURE COULD REACH 7×10^6 POUNDS PER YEAR BY 1990.
- OTHER SURFACE TRANSPORTATION APPLICATIONS DO NOT APPEAR TO BE SIGNIFICANT.

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PLAN FOR PHASE II

The Phase I results described in this report indicate that the applications of graphite composites in surface transportation are (in decreasing order of probable economic significance):

1. Passenger automobiles
2. Trucks
3. Railroad freight cars
4. Busses and light rail vehicles.

In Phase II it is proposed to concentrate on passenger cars, trucks and railroad freight cars.

Phase II will deal with specific economic, institutional, social and technological questions raised by the potential widespread use of composites in surface transportation. The purpose of Phase II will be to provide higher confidence quantitative estimates of the economic impacts of the uses of graphite composites, to identify the social impacts of their use, and to explore the institutional and technological factors that may be constraints to the use of the graphite composites. A vehicle design integration will be performed for the selected uses to determine the economic impacts at several levels of interest. Possible levels to be considered include the national level, the individual owner, the manufacturers and the suppliers. In this evaluation, life-cycle costs of the vehicle as well as factors of safety, comfort and consumer acceptance will be considered. Since it is likely that composites will be introduced over a period of years and that many years will be required for the replacement of the present noncomposite vehicle fleet, scenarios will be developed to estimate both the demand for vehicles and the rate of introduction of graphite composite materials into the vehicle fleet. Total savings will then be estimated on the basis of graphite composite usage and fleet evolution over the selected time horizon. The fleet model will be designed to enable rapid sensitivity analysis for alternative externalities, rates of introduction and usage.

PLAN FOR PHASE II

- PASSENGER AUTOMOBILES, TRUCKS, FREIGHT CARS
- DEVELOP SCENARIOS FOR INTRODUCTION OF GRAPHITE COMPOSITES AS FUNCTION OF TIME
- EVALUATE EFFECTS OF FACTORS SUCH AS SAFETY, COMFORT AND CONSUMER ACCEPTANCE
- ESTIMATE CHANGES IN VEHICLE LIFE-CYCLE COSTS FROM USE OF GRAPHITE COMPOSITES
- ESTIMATE ECONOMIC IMPACT ON OWNERS, MANUFACTURERS AND SUPPLIERS
- ESTIMATE ECONOMIC AND ENERGY BENEFITS OF GRAPHITE COMPOSITE USAGE

THE COMPOSITE MATERIALS INDUSTRY

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TYPES OF COMPOSITE MATERIALS

Composite materials are, by definition, composed of two (or more) distinct material components, each having a specific function and, acting together, offering properties which cannot be achieved by any of the components acting alone.

There are several types of fiber used in the modern composite materials. They are: aramid, boron, carbon and glass fibers.

Aramid is a generic name (assigned by FIC) for a family of aromatic polyamide fibers. Kevlar (made by DuPont) is the main representation of this group.

Boron fibers are made by boron deposition on tungsten filaments. The cost of boron fibers is much higher than costs of other fibers used in the high-performance composite materials.

Carbon fibers are produced from polyacrylonitrile, pitch or rayon precursors. Carbon fibers are commonly known as graphite.

Glass fibers are made from silicon carbide. They are not considered to be "advanced" fibers.

Hybrids combine two of the above families of fibers, utilizing and balancing their diverse properties.

Thermoset resins need curing time during the fabrication of composites and cannot change shape once cured.

Thermoplastic resins and the composite parts made from fibers using them can be reformed by the reapplication of heat and pressure.

TYPES OF COMPOSITE MATERIALS

- FIBERS:
- ARAMID
 - BORON
 - GRAPHITE
 - GLASS
 - HYBRID (ARAMID & CARBON, CARBON & GLASS, ETC.)

- MATRIX:
- THERMOSET RESINS
 - EPOXIES
 - PHENOLICS
 - POLYIMIDES
 - POLYESTERS
 - THERMOPLASTIC RESINS
 - POLYSULPHONES
 - POLYPHENYLENE SULFIDES
 - POLYETHER SULPHONES
 - THERMOPLASTIC POLYIMIDES

COMPOSITE MATERIALS = FIBERS & MATRIX

SUMMARY OF PHYSICAL PROPERTIES OF ADVANCED COMPOSITES

The mechanical, thermal, electrical, chemical and environmental properties of high-performance fibers and the composite materials in which they are used, can be favorably compared to those of steel, aluminum or fiberglass composites.

A quick survey of the physical properties reveals high tensile strength, high fatigue and creep resistance, high vibrational damping and high impact strength, which are combined with low specific density, low friction coefficient and low coefficient of thermal expansion. In addition, the advanced composite materials are electrically conductive, have good chemical resistance and are environmentally stable.

The physical properties of composite materials are described in greater detail in Appendix A.

SUMMARY OF PHYSICAL PROPERTIES OF ADVANCED COMPOSITES

MECHANICAL PROPERTIES

- HIGH TENSILE STRENGTH
- MED-HIGH MODULUS OF ELASTICITY
- LOW SPECIFIC DENSITY
- HIGH FATIGUE RESISTANCE
- HIGH CREEP RESISTANCE
- HIGH VIBRATIONAL DAMPING
- LOW FRICTION COEFFICIENT
- HIGH IMPACT STRENGTH

THERMAL, ELECTRICAL AND CHEMICAL PROPERTIES

- LOW COEFFICIENT OF THERMAL EXPANSION
- GOOD ELECTRIC CONDUCTIVITY
- CHEMICAL RESISTANCE

ENVIRONMENTAL PROPERTIES

- ENVIRONMENTAL STABILITY
- ENVIRONMENTAL RESISTANCE

PRESENT USE OF GRAPHITE FIBERS

Lightweight aircraft structural elements were the first application of newly developed high-performance materials. There are numerous parts on aircraft, spacecraft and missiles where the high specific strength and modulus are fully utilized. Not only weight was saved, but also the fabrication cost was lower regardless of the high cost of the material. Increasing use has recently been made in commercial aircraft. The aerospace industry has been a pioneer in the use of composites.

The largest current user of graphite composites is in the sports and recreational industry. Graphite golf shaft production reached more than one million in 1974. Graphite composite fishing rods utilize the excellent vibration damping characteristics. Tennis rackets, sail boats, skis, ski poles all utilize the favorable specific strength and specific modulus of graphite composites.

Industrial equipment is the most promising field of future growth. The first applications occur in high-speed rotating or oscillating machinery where weight, strength, fatigue and vibration limit machine operating speed and, therefore, productivity. Examples are various components of textile machines and cigarette machines. Gears and bearings made by injection molding and precision measuring instruments utilize high stiffness and strength, good resistance to fatigue and wear, and minimize errors introduced by temperature, pressure and vibration.

PRESENT USE OF GRAPHITE FIBERS

AEROSPACE APPLICATIONS

- AIRCRAFT
- SPACECRAFT
- MISSILES

NONAEROSPACE APPLICATIONS

- SPORTS AND RECREATIONAL EQUIPMENT
- MARINE EQUIPMENT
- INDUSTRIAL EQUIPMENT
 - GEARS AND BEARINGS
 - PRECISION INSTRUMENTS

PRODUCTION OF HIGH PERFORMANCE FIBERS

There are two types of high-performance fibers which have potential use in surface transportation. They are the graphite fibers and aramid fibers. The U.S. production of graphite fibers in 1976 was between 200,000 and 250,000 pounds. Union Carbide and Hercules make more than 95 percent of the total production. The aramid fibers will most likely be used in the form of hybrid composites. Their low cost will make the hybrids more economical. DuPont's Kevlar 49 is an aramid fiber having that potential.

There are several forms of graphite fibers which are used in manufacturing of composites. The continuous fibers are used for filament winding or pultrusion. Unidirectional prepreg (preimpregnated fiber) is made in 3-inch to 36-inch wide tapes and is used for lamination. The use of woven fabric results in quasi-isotropic properties of the composite which is, however, accompanied by a significant reduction in strength. Dry woven cloth or prepreg is used mainly for compression molding. Composites made from chopped fibers, which is the least expensive form of carbon fibers, retain many of the continuous fiber characteristics but in a substantially reduced degree. The reinforcement is discontinuous and the material has almost isotropic properties.

PRODUCTION OF HIGH PERFORMANCE FIBERS

GRAPHITE FIBERS: PRODUCTION: 200,000 - 250,000 POUNDS (1976)

PRODUCERS:

- HERCULES
 - UNION CARBIDE
 - CELANESE
 - GREAT LAKES
 - STACKPOLE
- } MORE THAN 95% OF ALL PRODUCTION

ARAMID FIBERS:

- DUPONT, 1976 PRODUCTION: 9,000,000 POUNDS

FORMS OF GRAPHITE FIBERS:

- CONTINUOUS FIBER (USED IN FILAMENT WINDING, PULTRUSION, ETC.)
- UNIDIRECTIONAL PREPREG (TAPE FOR LAMINATION)
- WOVEN FABRIC (DRY CLOTH OR PREPREG FOR LAMINATION)
- CHOPPED FIBER (FOR INJECTION OR COMPRESSION MOLDING COMPOUNDS)

CURRENT PRICES OF FIBERS AND RESINS

The current prices of the graphite fibers are compared with those of aramid fibers, glass fibers, steel and aluminum in the table given on the opposite page. The current prices of Union Carbide Thornel 300 fiber range from \$32/pound for commercial grade to \$105/pound for the high quality aerospace grade. The Hercules Magnamite fibers are priced from \$32/pound for AS-2 commercial grade to \$75/pound for high modulus grade. Both these fibers are made from polyacrylonitrile (PAN) fiber precursors with a base price of \$0.20/pound.

The recently introduced Magnamite AS-3 fiber has been manufactured by the existing fiber producing technology with additional improvements, which enabled Hercules to reduce the price to the \$18/pound range. The other recently introduced fiber, Union Carbide's Thornel P, is made from a pitch precursor with a base price of \$0.05/pound. The current price of the fiber is in the \$20/pound range. The properties of these new fibers are under constant development.

The prices of aramid fibers (DuPont Kevlar 49) range from \$4.5 to \$20/pound depending on the quality and form, while the prices of fiberglass are between \$0.5 and \$1/pound. The resins contribute very little to the cost of the composites (between \$0.40 and \$0.90/pound). Hybrid composites (aramid/graphite/resin) can bring a lower price tag and still preserve the properties of both reinforcing fibers.

The comparison with metals, i.e., carbon steel plate and bar, stainless steel or aluminum, shows the substantial difference in costs. However, the overall large volume manufacturing costs, lifetime costs, energy considerations and other reasons can change this picture and make graphite composites cost competitive with metals.

CURRENT PRICES OF FIBERS AND RESINS

<u>MATERIAL</u>	<u>MANUFACTURER</u>	<u>PRODUCT</u>	<u>PRICE (\$/lb)</u>	<u>DATE</u>
GRAPHITE FIBER	UNION CARBIDE	THORNEL 300 (WYP 15-1/0)	32	1/5/76
		THORNEL TYPE P (VSA-11)	20	11/15/76
	HERCULES	MAGNAMITE AS-2	32	2/1/76
		MAGNAMITE AS-3	18	3/1/77
ARAMID FIBER	DUPONT	KEVLAR 49	4.5 - 20	CURRENT
		NOMEX	N.A.	
GLASS FIBER		E-GLASS	0.50	CURRENT
			0.5 - 1	CURRENT
RESINS	CIBA-GEIGY	POLYESTER	0.40 - 0.70	CURRENT
		EPOXY	0.75 - 0.9	CURRENT
STEEL	PRICES BY AMERICAN METAL MARKET	CARBON STEEL PLATE	0.15	CURRENT
		CARBON STEEL BAR	0.21	CURRENT
		STAINLESS STEEL	0.78	CURRENT
ALUMINUM	PRICES BY AMERICAN METAL MARKET	99.5% ALUMINUM	0.53	CURRENT

GRAPHITE FIBER COST: HISTORY AND PROJECTIONS

The high modulus graphite fibers were introduced on the commercial market in the early 1960s. They were made by the pyrolysis of a rayon precursor yarn. They were used exclusively in aerospace and the average cost of graphite fibers was around \$500/pound. The production volume was several hundred pounds a year.

The aerospace industry needed a fiber with a balanced tension and compression moduli and a higher elongation. The polyacrylonitrile (PAN) fiber is a basic material which changes by oxidization, carbonization and graphitization into a graphite fiber of outstanding qualities. The volume of production increased and the material became cost effective.

In the early 1970s the first sporting goods and recreation industry applications of PAN increased the volume of production to 11,000-20,000 pounds/year range and reduced prices to \$150 to \$200/pound.

The volume of production in 1976 was between 200,000-250,000 pounds. The price for a commercial grade fiber was \$32/pound. For high quality aerospace grade fiber, prices were as high as \$100/pound.

The recently introduced graphite fibers, namely Hercules AS-3 fiber and Union Carbide Thornel P fiber, will most probably be the fibers used in large volumes in the future. The table on the opposite page shows the price projections if the volume of production increases to several million pound per year. The prices of both fibers would move into a range (\$5 to \$6/pound) where they would be highly competitive with metals.

There are other considerations which may offset the higher cost of graphite composites. The properties of composites permit a simpler design with fewer parts and lower labor costs. Beyond manufacturing, the lifetime cost of operating and maintaining the part are also important.

Repairability depends on the component design and the type of failure. Present techniques using woven fabric, fast curing resins and fillers could be successfully applied.

GRAPHITE FIBER COST: HISTORY AND PROJECTIONS

<u>YEAR</u>	<u>VOLUME (lbs)</u>	<u>PRICE (\$/lb)</u>	<u>COMMENT</u>
1963	N.A.	500	FIRST AEROSPACE APPLICATIONS
1970	11,000 - 20,000	150 - 200	FIRST SPORTING GOODS APPLICATIONS
1976	200,000 - 250,000	32 - 40	
1977	IF 1,000,000	11	HERCULES AS-3 PRESENT TECHNOLOGY
	IF 1-2,000,000	8 - 10	U.C. THORNEL P IS USED, PRICES IN 1977 DOLLARS
	IF 10,000,000	7	HERCULES AS-3
	IF 50,000,000	6	HERCULES AS-3
>1980	5-10,000,000	>5	U.C. THORNEL P AUTOMOTIVE APPLICATIONS

SOURCES: HERCULES, UNION CARBIDE

FABRICATION OF COMPOSITE MATERIALS

The aerospace industry has a low production volume and is very labor intensive. The manufacturing processes consist mainly of hand layups and long-cure cycles. The surface transportation industries, mainly the automotive industry, have very high volumes of production and require fast rates of production. The most promising techniques for use in the automotive industry application are listed below:

- Filament winding - simultaneous and continuous application of fibers and resins; suitable for fabrication of shafts and torsion bars.
- Pultrusion - continuous production of products with a constant cross-section; availability of curved shapes; production rates of 15 feet/minute.
- Compression molding - prepregs (tapes, woven sheets) are formed into various shapes at 2,000 psi pressure and 650-675°F temperature for 3 to 4 minutes.
- Injection molding - high volume, low labor costs, good reproducibility; fibers 1/4 to 1/2 inch long in chopped form. Experiments with longer fibers (2 to 5 inches) and directional orientation of fibers; high tool and die costs.
- Reaction injection molding (RIM) - low tooling costs, low energy usage, possibility of making all kinds of shapes; previously limited to unreinforced plastics; new mixing heads allow use of fibers in making high modulus parts.
- Stamped thermoplastics - one of the most promising techniques using existing stamping equipment; rapid production rates; problems because of a lack of stretch forming of composites.

The joining of composite material parts is accomplished by a secondary adhesive bonding using fast-curing resins in a gun-type soldering. Experiments have been made with laser and ultrasonic welding. Existing techniques are successfully used in the machining of the components. The finishing of the surfaces depends on the fabrication process. There are some difficulties with parts made by compression molding (microporosity, small cracks), while excellent finish is obtained by injection molding or RIM. Conductivity of carbon fibers results in excellent electrostatic paintability.

FABRICATION OF COMPOSITE MATERIALS

FABRICATION PROCESSES:

- FILAMENT WINDING
- PULTRUSION
- COMPRESSION MOLDING
- INJECTION MOLDING
- REACTION INJECTION MOLDING
- STAMPED THERMOPLASTICS

POST-FABRICATION OPERATIONS:

- JOINING
- MACHINING
- FINISHING
- PAINTING
- REPAIRABILITY

RECYCLABILITY:

- NO ACTIVITY REPORTED

COMPONENT DESIGN WITH ADVANCED COMPOSITES

The design of components using the composite materials would most probably follow two simultaneous paths. The first would be the direct substitution method, where some components, currently made from metals, could be designed from composites. A typical example would be the drive shaft, which is of a rather simple design and can be easily connected to other metal components; or the various support brackets (radiator, air conditioning, etc.) which are not the most stressed parts. This approach provides a good learning period for designers and engineers.

Simultaneously, the "clean sheet of paper" design approach could be followed as a research and development effort. The subassembly components could be designed fully utilizing the properties of composites. For example: a component previously made from several parts could be manufactured as one piece. This would substantially reduce the labor cost of assembly.

The basic difference between designs of components using metals and composite materials is that the metals are isotropic materials while composites are anisotropic materials. The component design becomes more sophisticated when the different material properties in different directions and high stiffness-to-weight and high strength-to-weight ratios are fully utilized. Designs must be made considering the different possible modes of failure. Secondary benefits, such as reduced weight, noise, vibration, etc., require additional changes in different parts. A final result will be the iterative optimization of a new, more efficient design.

The area of design and analysis is where the experience of aerospace industry can have the greatest impact. The advanced state-of-the-art methods used for the aerospace design, such as three dimensional finite element computer programs, can be utilized.

COMPONENT DESIGN WITH ADVANCED COMPOSITES

IN GENERAL

- DIRECT SUBSTITUTION METHOD → LEARNING CURVE
- NEW "CLEAN SHEET OF PAPER" DESIGN FULLY UTILIZING THE PROPERTIES OF COMPOSITES:
(EXAMPLE: CAR-DOOR, BUMPER SYSTEM, ETC.)

METAL

- ISOTROPIC MATERIAL

COMPOSITES

- ANISOTROPIC MATERIAL → MORE INVOLVED DESIGN
 - UTILIZATION OF DIFFERENT PROPERTIES
IN DIFFERENT DIRECTION
 - DIFFERENT MODES OF FAILURE
 - HIGH STIFFNESS/WEIGHT RATIO
 - HIGH STRENGTH/WEIGHT RATIO
- SECONDARY BENEFITS
 - REDUCED WEIGHT
 - REDUCED VIBRATION
 - REDUCED NOISE

} ITERATIVE
OPTIMIZATION OF
A NEW DESIGN
- IMPACT OF AEROSPACE INDUSTRY IS GREATEST IN THE DESIGN EXPERIENCE

CURRENT ACTIVITIES IN THE USE OF GRAPHITE COMPOSITES IN SURFACE TRANSPORTATION

Experimental applications of graphite composites have been made in the automotive industry, along with the fast-growing use of unreinforced plastics in nonstructural applications.

There are currently several components using graphite fiber composites which are in a prototype testing stage. These are leaf springs, drive shafts, car-door intrusion beams, truck frame elements and wheels. There are many possible applications of composites in the design of automobiles and trucks. The four major areas of applications are engine, drive train, chassis and suspension, and body and structure. Some of the candidate components are listed in the table on the opposite page.

It should be noted that the successful replacement of one metal part often leads to secondary benefits. For example, the graphite/epoxy filament-wound drive shaft has been extensively tested in the last two years. Besides having excellent torsional strength, it requires less balancing, reduces the noise level because of the graphite composite's good damping characteristics, and affords a smoother ride.

The American Railway Car Institute has reported a development of a prototype railroad tank car using the composite materials. There are several areas in the railroad industry, and other surface transportation industries, where the application of composites are feasible. However, almost no activity has been reported.

CURRENT ACTIVITIES IN THE USE OF GRAPHITE COMPOSITES IN SURFACE TRANSPORTATION

AUTOMOBILES AND TRUCKS:

- THE MOST ACTIVE INDUSTRY
- UTILIZING THEIR FAST GROWING SHIFT INTO USING UNREINFORCED PLASTICS FOR NONSTRUCTURAL APPLICATIONS
- EXPERIMENTS AND TESTING OF REINFORCED COMPOSITES (SOME PROTOTYPE TESTING)
 - LEAF SPRINGS
 - DRIVE SHAFTS
 - CAR-DOOR INTRUSION BEAMS
 - TRUCK FRAME ELEMENTS
 - WHEELS
- FUTURE APPLICATIONS
 - ENGINE AREA (PUSH AND CONNECTING RODS, ROCKER ARMS, OIL PAN, ETC.)
 - DRIVE TRAIN AREA (SHAFTS, AXLE AND AXLE HOUSING, YOKE, TRANSMISSION HOUSING)
 - CHASSIS & SUSPENSION
 - LEAF SPRINGS
 - FRAME COMPONENTS
 - BRAKE LININGS
 - WHEELS
 - SECONDARY STRUCTURAL BODY COMPONENTS
 - AIR COND., TRANSMISSION & RADIATOR SUPPORTS AND BRACKETS
 - BUMPER BEAMS AND WHOLE BUMPER SYSTEMS

RAILROAD TRANSPORTATION: DEVELOPMENT OF A RAILROAD TANK CAR (REPORTED BY ARCI)

OTHER TRANSPORTATION: NO ACTIVITY REPORTED

AUTOMOBILE INDUSTRY AND SHIFT TO USE OF PLASTICS

The recent shift to the use of plastics in the automotive industry can clearly be demonstrated by the increase in the use of plastics per average passenger car. The use of plastics has grown from a few pounds in the 1950s to 180 pounds for an average 1977 model. The future growth of the use of unreinforced plastics is expected to be between 30 and 40 pounds in the average car in the next few years.

The introduction of graphite composites, will not drastically alter this picture in the near future. It is expected that the use of graphite composites will be around 5 pounds per average car in 1985 and around 90 pounds per average car in 1990.

How will all the processing be done? Some manufacturing will be done by custom processors, using compression molding, reaction injection molding (RIM) and pultrusion (manufacturers of graphite fibers offer various pultruded shapes). The rest of the composite material components will be manufactured by the auto makers themselves using techniques such as injection molding and stamping from thermoplastics. The trend in manufacturing of plastic components has been clearly established in the recent years, and is supported by heavy purchasing of injection molding machines by the four major U.S. auto companies. The most recent development in the plastics processing capabilities of auto makers is listed in the table on the opposite page. In the fall of 1976, GM had 1150 injection units, Ford had 350, AMC had 130 and Chrysler only 9 (source: Modern Plastics).

The newly acquired plastics processing machinery is capable of using reinforcing fibers. The mixing head of injection machines can use fibers up to 2 inches long. The use of graphite fibers represents no problem because of the good lubricity of graphite. The currently used stamping machines can be used with a few adjustments to pressures, temperatures and tolerances.

AUTOMOBILE INDUSTRY AND SHIFT TO USE OF PLASTICS

- PAST USE OF PLASTICS - A FEW POUNDS PER AVERAGE CAR IN 1950s
- PRESENT USE OF PLASTICS - AVERAGE 1977 MODEL TOTAL OF 180 LBS (10 LBS MORE THAN 1970)
- GROWTH IN UNREINFORCED PLASTICS - 30-40 LBS PER AVERAGE CAR IN 1979, 1980
- ESTIMATES OF GRAPHITE REINFORCED COMPOSITES
 - 1985: 5 lbs/AVERAGE CAR
 - 1990: 90 lbs/AVERAGE CAR
- MANUFACTURING BY - CUSTOM PROCESSORS, ESPECIALLY: COMPRESSION MOLDING, RIM AND PULTRUSION
 - AUTOMAKERS THEMSELVES, ESPECIALLY: INJECTION MOLDING STAMPED THERMOPLASTIC
- GROWING INVESTMENT BY AUTOMAKERS IN PLASTICS MANUFACTURING
 - FORD: A NEW PROCESSING FACILITY (READY FOR 1978)
 - CHRYSLER: ACQUISITION OF U.S. STEEL'S MOLDED PLASTICS OPERATION
 - GM AND AMC: HEAVY PURCHASING OF INJECTION MOLDING MACHINES
- NEW MACHINERY IS CAPABLE OF USING REINFORCING FIBERS IN INJECTION MOLDING

PASSENGER ACCEPTANCE OF USE OF COMPOSITES

Passenger acceptance of the graphite fiber reinforced composites can be gauged by the vehicles appearance, noise, ride and handling, and safety aspects.

The vehicles appearance will not be influenced by use of graphite composites. Most graphite composites will be hidden from sight because of their function (drive shaft, support brackets, etc.). The visible parts will be unrecognizable due to the excellent paintability of the graphite composites. Poor sales of 1977 cars with RIM "nonbright" bumpers and fascias indicate a potential passenger acceptance problem. Technologies are being developed to have "bright" flexible plastic parts.

The use of graphite composites will result in general reduction of vehicle noise (ignition noise, transmission vibrations) because of the composites excellent vibrational damping and sound reducing characteristics. Improvements in ride and handling will be realized by the use of graphite leaf springs, which reduce the unsprung weight. The safety aspects and crash worthiness requirements should be met without difficulties. Different modes of graphite composites failure must be examined in determining the crash worthiness. The flammability and toxicity of graphite composites (especially that of resins) must be further examined.

PASSENGER ACCEPTANCE OF USE OF COMPOSITES

- APPEARANCE
 - NONEXTERIOR PARTS: NO DIFFERENCE
 - EXTERIOR PARTS: UNRECOGNIZABLE
 - EXCEPT BUMPER SYSTEM AND FASCIAS (POOR INITIAL SALES OF 1977 CARS WITH "NONBRIGHT" RIM PARTS INDICATED A PROBLEM AREA)
 - TECHNOLOGY BEING DEVELOPED TO HAVE "BRIGHT" PLASTIC PARTS
- NOISE
 - GENERAL REDUCTION OF NOISE (DRIVE SHAFTS, IGNITION NOISE, ETC.)
BECAUSE OF VIBRATIONAL DAMPING AND SOUND DEADENING PROPERTIES
- IMPROVEMENTS IN RIDE AND HANDLING
 - EXAMPLE: LIGHT WEIGHT SPRINGS REDUCE THE UNSPRUNG WEIGHT
- SAFETY ASPECTS
 - UNCHANGED

APPLICATION OF COMPOSITES TO
SURFACE TRANSPORTATION VEHICLES

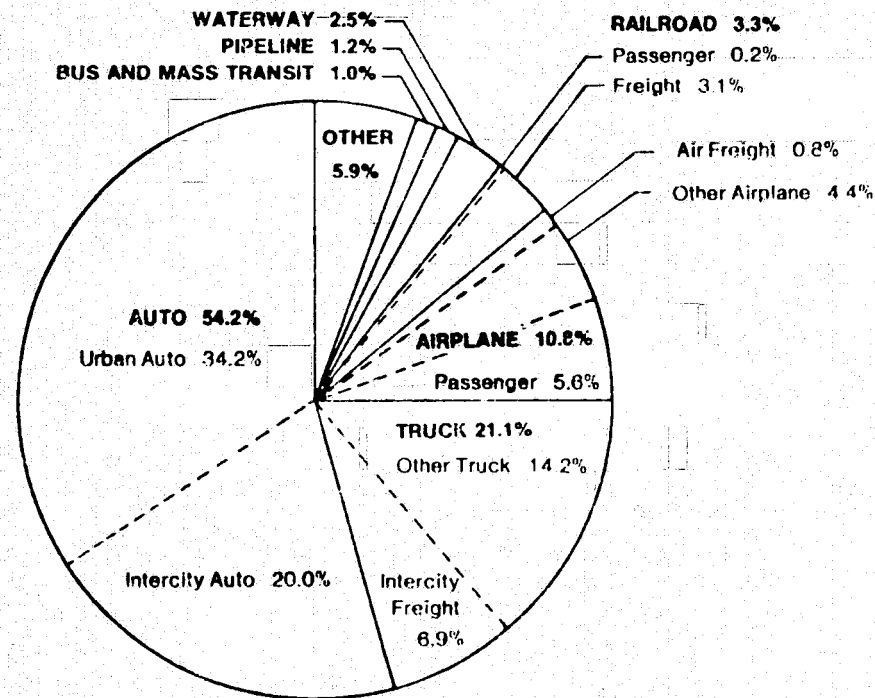


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ENERGY CONSUMPTION BY TRANSPORT MODE, 1970

One of the principal benefits of the use of composite materials in ground transportation is the significant energy savings that may be possible through weight reduction. The breakdown of energy consumption by transportation mode shown indicates that the greatest areas for concentration are the automobile and truck sectors. Except for size, the automobile fleet is generally homogeneous, so that in this study we can consider the application of composites to a standard or average automobile. Although the truck fleet is highly heterogeneous, both the energy consumption and vehicle production are concentrated in light-duty (classes I and II) and heavy-duty (class VIII) truck types. Applications of composite materials, since they may increase the economic productivity of the railroad industry, may result in indirect energy benefits to this mode of transportation. These benefits may prove to be vital to our energy future.

ENERGY CONSUMPTION BY TRANSPORT MODE, 1970

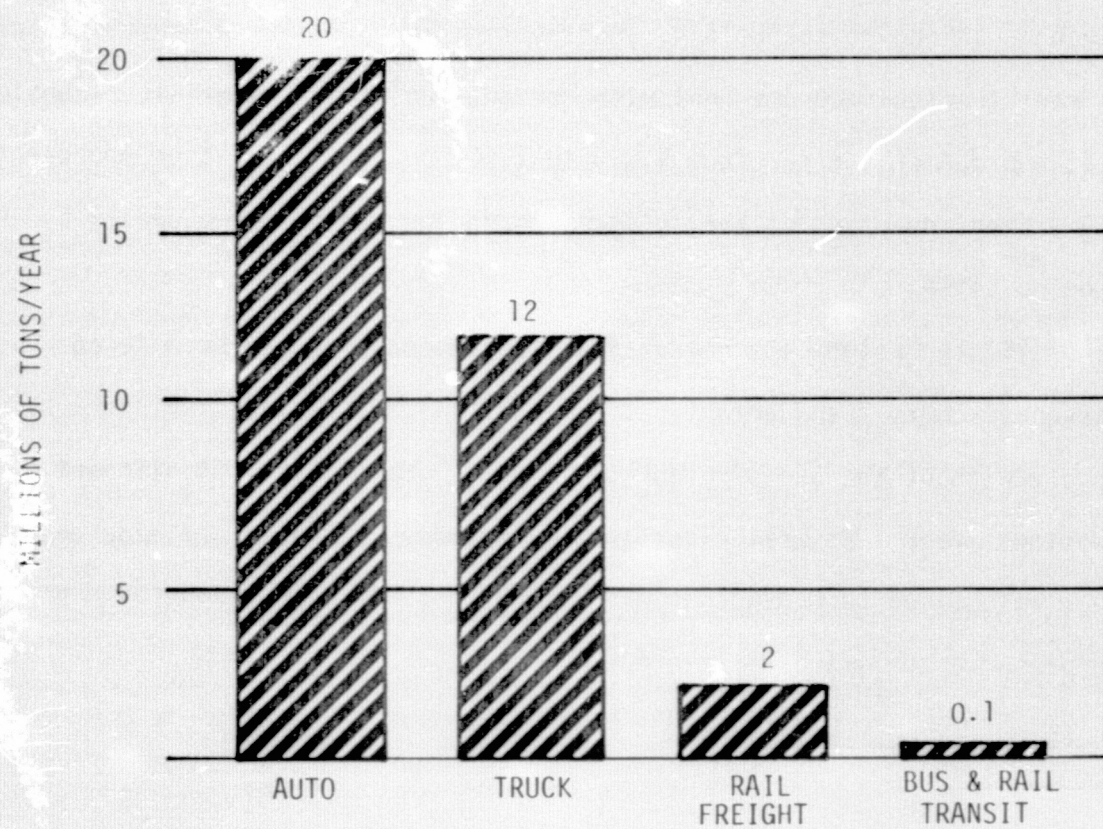


SOURCE: LUTIN, J.M., COMPARISON OF ENERGY SAVINGS FOR WORK TRIPS, PRINCETON UNIVERSITY TRANSPORTATION PROGRAM, 1974.

ANNUAL VEHICLE PRODUCTION GROSS MATERIAL USAGE

The potential market size for composite materials, in the various modes, may be estimated from the chart on the opposite page. The automobile and truck modes are clearly the most significant. Rail freight is seen to be significant due to the heavy individual vehicle weight. The actual number of freight vehicles produced is much smaller than that of motor vehicles. At least 50 percent of the weight of each of these vehicles is steel. In those applications where high strength is required, composite materials may provide a weight and energy efficient alternative to the continued use of steel.

ANNUAL U.S. VEHICLE PRODUCTION GROSS MATERIAL USAGE

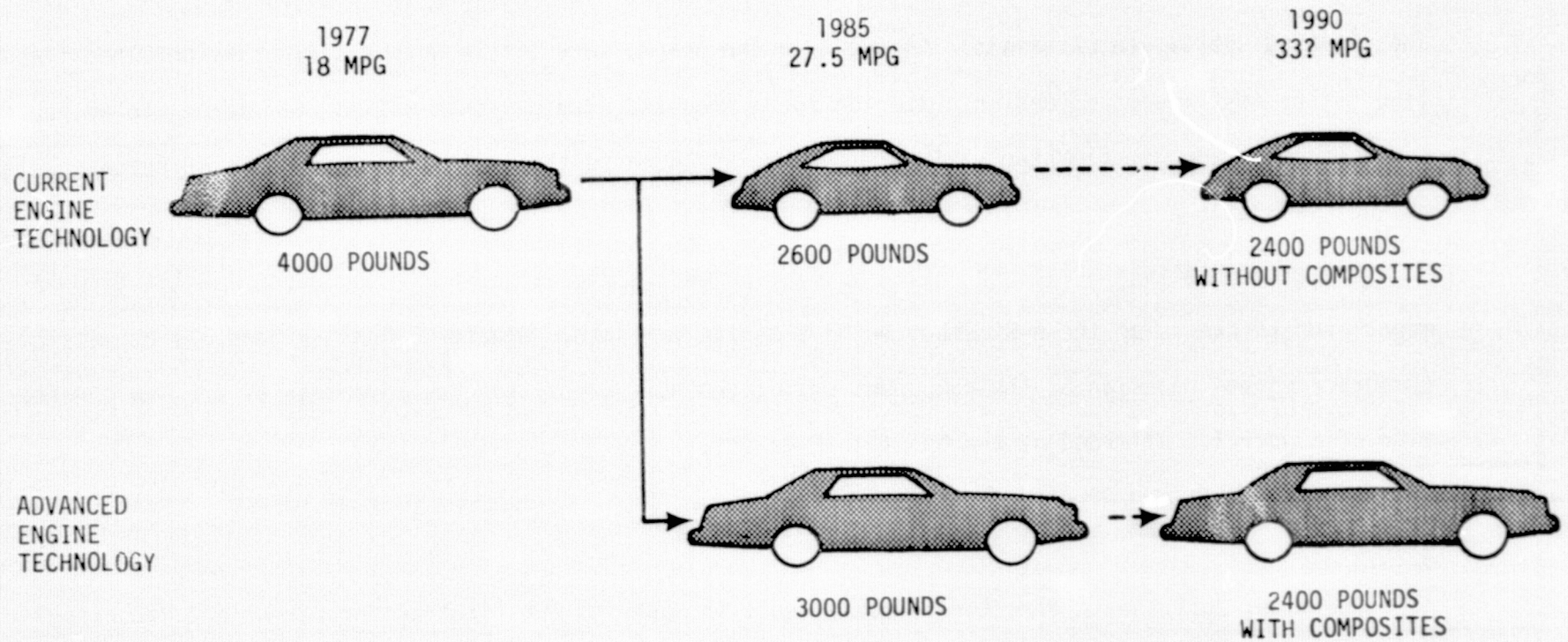


FUTURE AUTO WEIGHT TRENDS

The major driving force for design change in the automobile industry is the legislated goal of 27.5 MPG fleet average required of each automobile manufacturer. This goal will be met through downsizing of the vehicle fleet, changes in engine technology, and substitution of light weight materials in existing vehicle designs. To meet the fuel economy goal with current engine and materials technology would require a downsizing of the standard American car from 4,000 to 2,600 pounds, the latter representing a Pinto-sized automobile. By taking advantage of the advances in engine technology expected by 1985 an average of 3,000 pounds may be possible.

Through the use of lighter weight advanced materials the consumer may be offered a larger car which will provide more passenger comfort and potentially greater safety. Weight savings achieved by 1985 will be achieved largely without the use of graphite composite materials. Significant incentive for the use of graphite composites after 1985 will exist if fuel economy standards are made even more demanding. If the legislated goal was raised to a hypothetical 33 MPG in 1990, composites could provide sufficient weight reductions to preserve the standard size car.

FUTURE AUTO WEIGHT TRENDS



COMPARISON OF STRUCTURAL CHARACTERISTICS OF ALUMINUM AND MILD STEEL THIN-WALLED BEAM MEMBERS

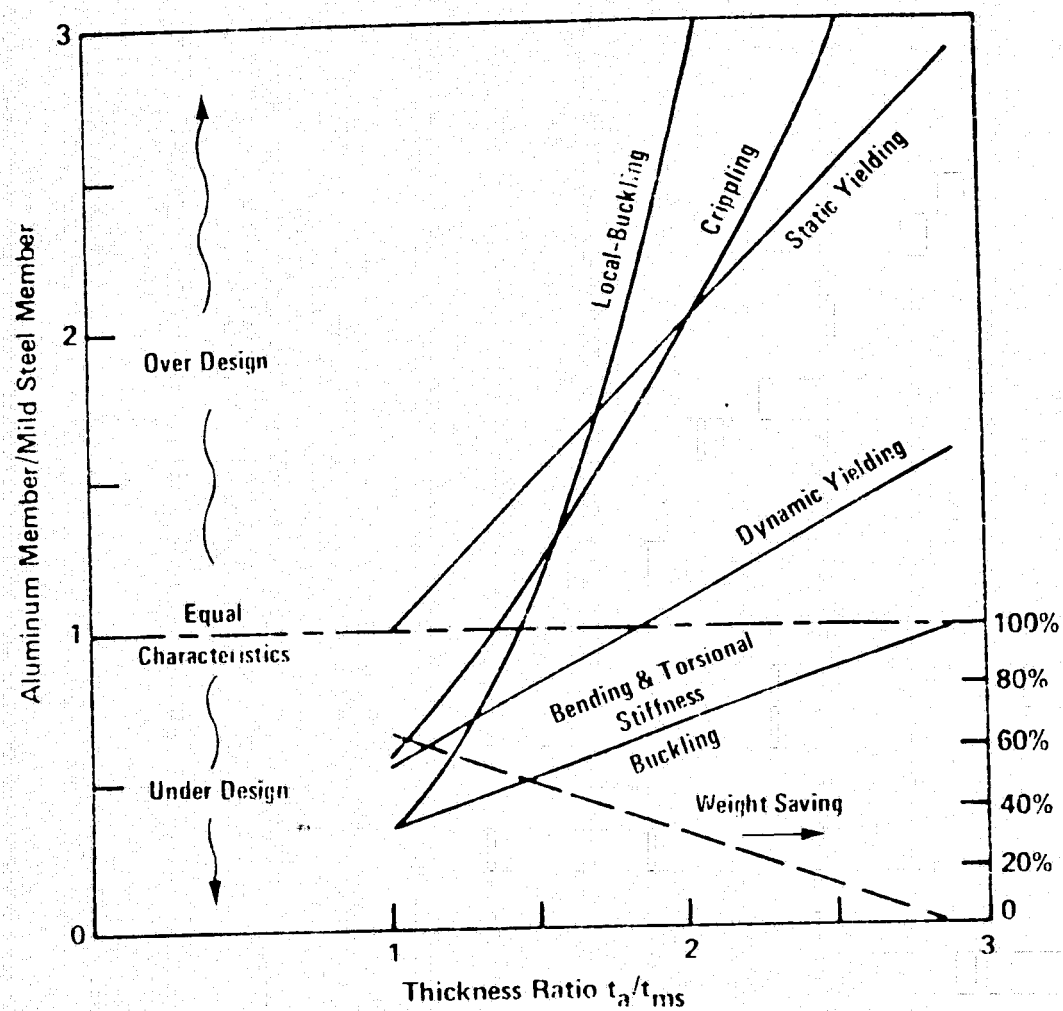
Estimation of the potential for weight savings through material substitution is a complex process. The potential weight savings for an individual part is a function of the structural characteristics of the part, the design criterion that is considered to be limiting, and the properties of the original and proposed substitute materials. As shown in the graph, very little weight savings is obtained if buckling is the most important design criterion for a proposed aluminum thin-walled beam member to be substituted for one made of mild steel. Should dynamic yielding be the limiting criterion, a 40 percent weight savings is possible.

These calculations are based on the assumption that a direct geometric component substitution is made, with thickness of the new member being a design variable. Greater weight savings may be possible through complete redesign of the component or integrated assembly to take advantage of the new combination of properties afforded by the substitute material.

Source:

Chang and Justusson, "Structural Requirements in Material Substitution for Car-Weight Reduction"
General Motors Research Laboratory, Report GMR-2019, February 1976.

COMPARISON OF STRUCTURAL CHARACTERISTICS OF ALUMINUM AND MILD STEEL THIN-WALLED BEAM MEMBERS



MATERIAL SELECTION IN ADVANCED DESIGN AUTOMOBILE

Between now and 1985, major substitutions of materials will take place in the American automobile. In general all nonstructural elements are candidates for material substitution from steel and zinc die castings to plastics and aluminum. Major load bearing components will continue to be steel, with some substitution of high strength steel alloys and aluminum. Only components of complex geometry that must endure high temperature environments will continue to be made from cast iron. In the post-1985 period the weight of the remaining steel elements may be reduced through substitution of graphite composite components or through graphite reinforcement of steel beams with reduced cross-section. The material selection shown in the chart assumes that composites will be used primarily as substitutes for steel, where the greatest potential for weight reduction exists and aluminum and plastic alternatives are not satisfactory.

MATERIAL SELECTION IN ADVANCED DESIGN AUTOMOBILE

COMPONENT AREA	CAST IRON	STEEL & HS ALLOYS	ALUMINUM	PLASTICS	GRAPHITE COMPOSITES
UPPER BODY:					
STRUCTURE		✓			✓
HOOD & DECK			✓	✓	
DOOR		✓	✓	✓	✓
TRIM & SEATS				✓	
LOWER BODY:					
RAILS & SILLS		✓			✓
CHASSIS:					
POWER PLANT	✓	✓	✓		
FINAL DRIVE		✓	✓		✓
FORESTRUCTURE		✓			✓
SUSPENSION		✓	✓		✓
STEERING, BRAKES				✓	
WHEELS & TIRES		✓	✓	✓	
EXHAUST & FUEL				✓	
BUMPERS		✓		✓	✓

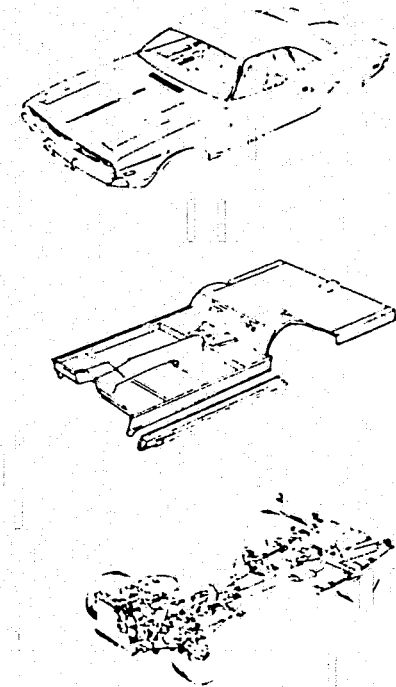
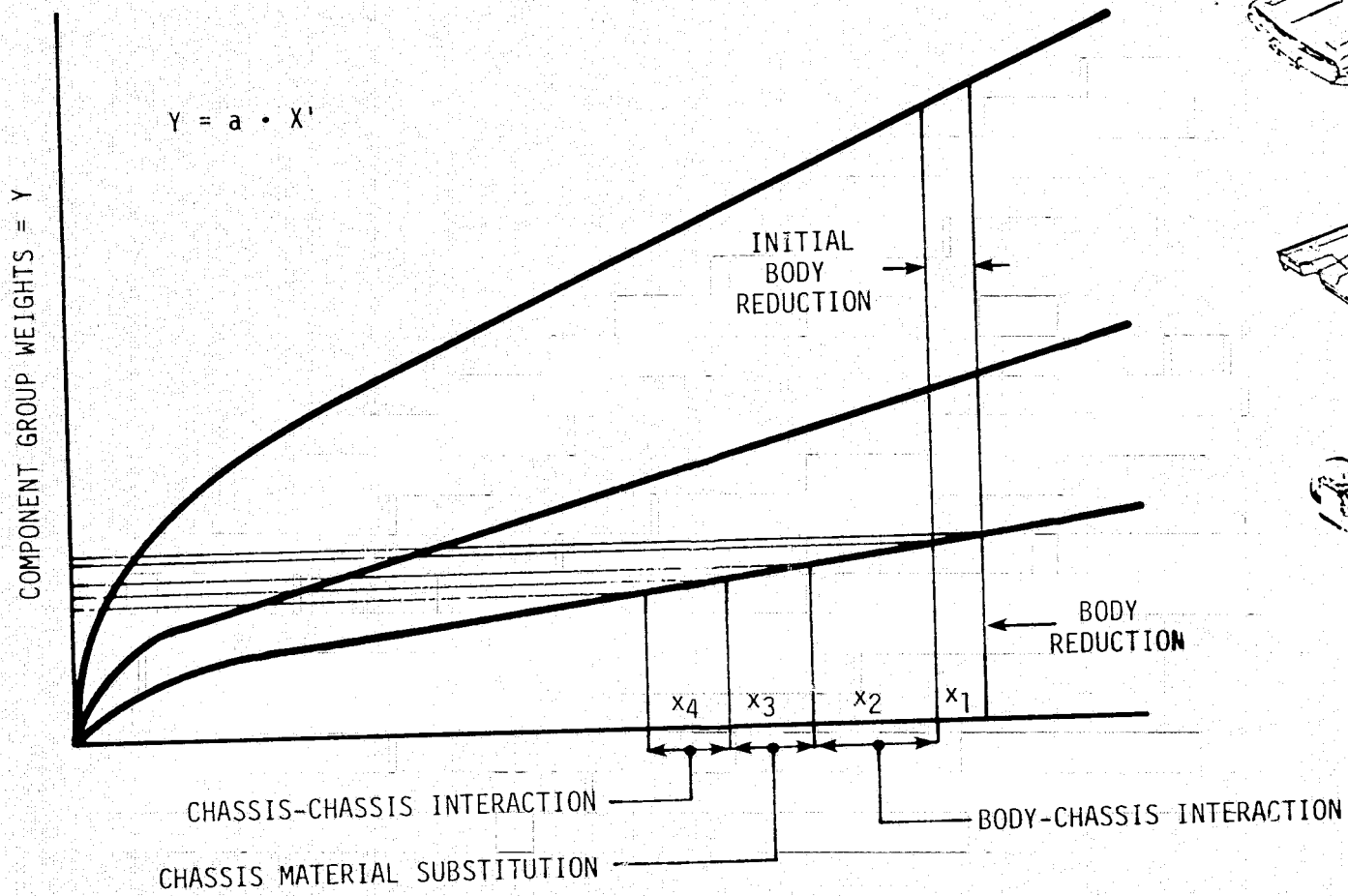
AUTOMOBILE INTERACTING WEIGHT MODEL

Potential weight savings achieved through material substitution are greater than those afforded by direct component and weight comparisons. A significant synergistic weight savings is possible through interaction of the design of various subassemblies in the automobile. In the interacting weight model used in this study, the upper body is studied first to estimate the weight savings potential in this subassembly. The reduced weight of the upper body lowers the strength requirement of the lower body, thereby reducing its weight prior to material substitution. The material substitution in the lower body is then added to the total weight reduction. This will reduce the strength requirement in the chassis and horsepower requirement in the power plant and drive train. Material substitution is applied finally to the chassis assembly group.

Source:

Adams, DiCello, Hoppe, Kasper, Keisoglou, and McVinnie, "High Strength Materials and Vehicle Weight Reduction Analysis". SAE Paper Number 750221, 1975.

AUTOMOBILE INTERACTING WEIGHT MODEL

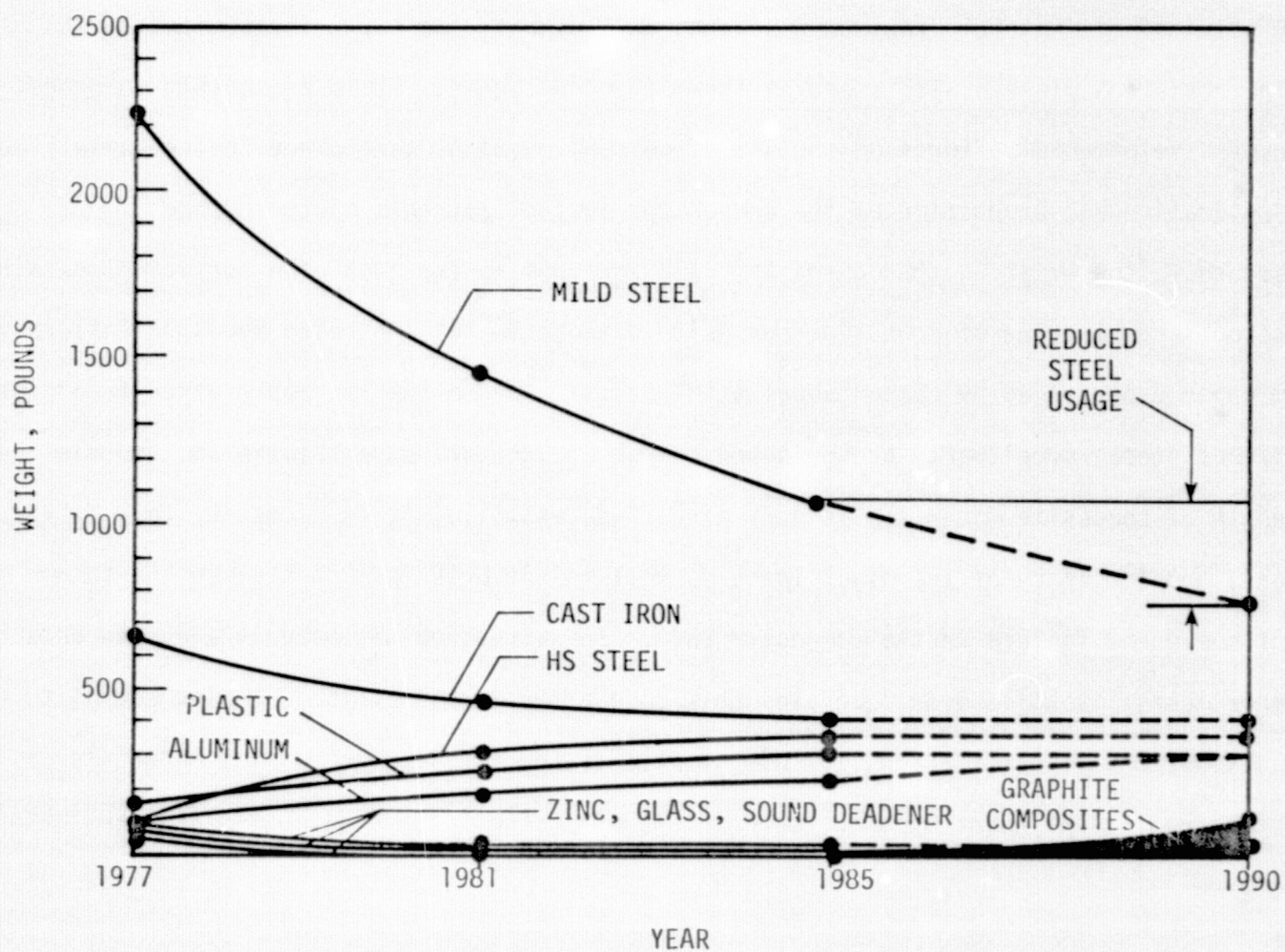


MATERIALS USAGE IN TYPICAL STANDARD AUTO TO 1990

The result of our material substitution analysis in the standard automobile is shown as a function of time. The use of relatively heavy zinc, glass, and sound deadening material is minimized or eliminated by 1985. The use of cast iron is reduced to applications in the power plant and other high temperature areas. The use of mild steel is reduced dramatically through the substitution of plastic and aluminum for nonstructural elements, and through downsizing and interactive effects. High strength steel is used in limited quantities for structural applications.

By 1985, most material substitutions possible with contemporary materials will have reached a steady state, with the exception of the use of aluminum in the power plant, which has the longest development and tooling lead time. In the post-1985 period up to 91 lbs. of graphite composite may be substituted for some of the remaining steel in the car structure. The analysis to support this estimate is shown in Appendix B. It is important to note that most of the reduction in steel weight will be achieved prior to the introduction of graphite composites in significant quantities. Graphite may become the leading substitute material after the less difficult material substitutions have been exhausted.

MATERIALS USAGE IN TYPICAL STANDARD AUTO TO 1990



BARRIERS TO USE OF COMPOSITES BEFORE 1985

A number of factors will limit the application of graphite composites in automobiles to less than 5 lbs. per car before 1985. One major factor limiting this application is that the automobile companies are currently committing their maximum research, development, and capital resource, to the major vehicle and engine revisions planned with state-of-the-art technologies. It is reasonable to expect that significant developmental efforts on the use of composites might take place in the early 1980s, leading to the application and production of the composites in the last half of the decade.

A second factor limiting the composites' applications is the lack of a sufficient data base on composite design. Testing of prototype composite components has indicated modes of failure very different from those experienced by conventional steel parts. Due to the isotropic strength and stiffness properties of steel, steel parts are designed to support the principal static and dynamic loads. Because the strength of composite materials is very direction-sensitive, it is necessary to know the magnitudes, directions, and frequency of the minor loads as well as the principal ones since the former may be the source of component failure in the composite part. Industry does not have an adequate data base on these minor loads; it will need to develop this base prior to use of load bearing composite parts.

As discussed in other sections in this study, widespread use of composite materials in the automobile industry is contingent upon the development of cost effective materials and manufacturing processes.

BARRIERS TO USE OF COMPOSITES
BEFORE 1985

- MAJOR COMMITMENTS IN INDUSTRY TO ENGINE CHANGES, DOWN SIZING, AND MATERIAL SUBSTITUTION WITH KNOWN TECHNOLOGY
- INSUFFICIENT DATA BASE ON COMPOSITE COMPONENT DESIGN
- HIGH COST OF MATERIALS AND MANUFACTURING PROCESSES

UNCERTAINTIES AFFECTING POST-1985 USE OF COMPOSITES

The incentive for the use of composite materials in automobiles in the post-1985 period is not clear. Composite materials may be essential if fuel economy standards that are more demanding than the 1985 standard are enacted. Pressure for composite material development may result even with the current 1985 standard, should the goals for vehicle weight reduction and advanced engine technology not be achieved.

The response of the public to a shift in manufacturing towards smaller cars is uncertain. In the face of the currently high gasoline prices and the increased energy awareness, the demand for full size cars remains high. The public may be willing to pay a premium price for a full size car that meets the enacted standards. The public may also not be willing to accept the possible increase in traffic fatalities that could accompany the increased use of small cars.

UNCERTAINTIES AFFECTING POST - 1985 USE OF COMPOSITES

- FUTURE FUEL ECONOMY STANDARDS
- LIMITS OF WEIGHT REDUCTION AND ENGINE TECHNOLOGY
- IMPACTS OF SMALL CARS ON SAFETY
- DEMAND FOR SMALL VS. LARGE CARS

AUTO INDUSTRY COMPOSITE MATERIALS COMPONENTS IMPLEMENTATION SCENARIO

The first graphite composite parts will be direct substitutions for their steel counterparts, such as drive shafts, leaf springs, or side rail reinforcements. If the initial programs are successful, later subassembly design may be reoptimized to take advantage of the material properties. During the initial production phase raw material production and part fabrication will be implemented by manufacturers outside the automobile industry, following the model established for use of conventional plastics in automobiles. When the production scale becomes sufficiently large to make vertical integration economically beneficial, the automobile companies may take over the part fabrication phase. The automobile manufacturers probably will continue to buy fiber and matrix raw materials from the outside.

AUTO INDUSTRY
COMPOSITE MATERIAL COMPONENTS
IMPLEMENTATION SCENARIO

	COMPONENT DESIGN	RAW MATERIAL PRODUCTION	PART FABRICATION
INITIAL PHASE (1985-1990)	DIRECT REPLACEMENT	OUTSIDE	OUTSIDE
LONG-TERM PHASE (1990-)	OPTIMIZED INTEGRATED DESIGN	OUTSIDE	VERTICAL INTERGRA- TION IF ECONOMICALLY BENEFICIAL

APPLICATIONS TO HEAVY-DUTY TRUCKS AND RAIL FREIGHT

Fabrication of graphite composites for trucks and rail freight vehicles is analogous to that for automobiles, except that a greater emphasis is placed on the direct economic benefits accrued to the substitution. Vehicle downtime is a critical parameter to freight system economics; composite material substitution may be justified if these materials can live up to their potential lifetimes: two to three times longer than those of their steel counterparts. Since it is the objective of the freight carrier to operate at the fully loaded limit of the road or rail bed, reduced weights for the empty vehicle will be replaced by increased payloads. This will increase the vehicle productivity, requiring fewer vehicles to transport the same number of ton-miles of freight. The energy efficiency of these modes in ton-miles per gallon will also increase.

APPLICATIONS TO HEAVY-DUTY TRUCKS AND RAIL FREIGHT

- DIRECT ECONOMIC BENEFITS
- MINIMIZE ROLLING STOCK DOWNTIME
- INCREASED PAYLOADS THROUGH REDUCED TARE WEIGHTS
 - INCREASED VEHICLE PRODUCTIVITY
 - INCREASED TON-MILE PER GALLON

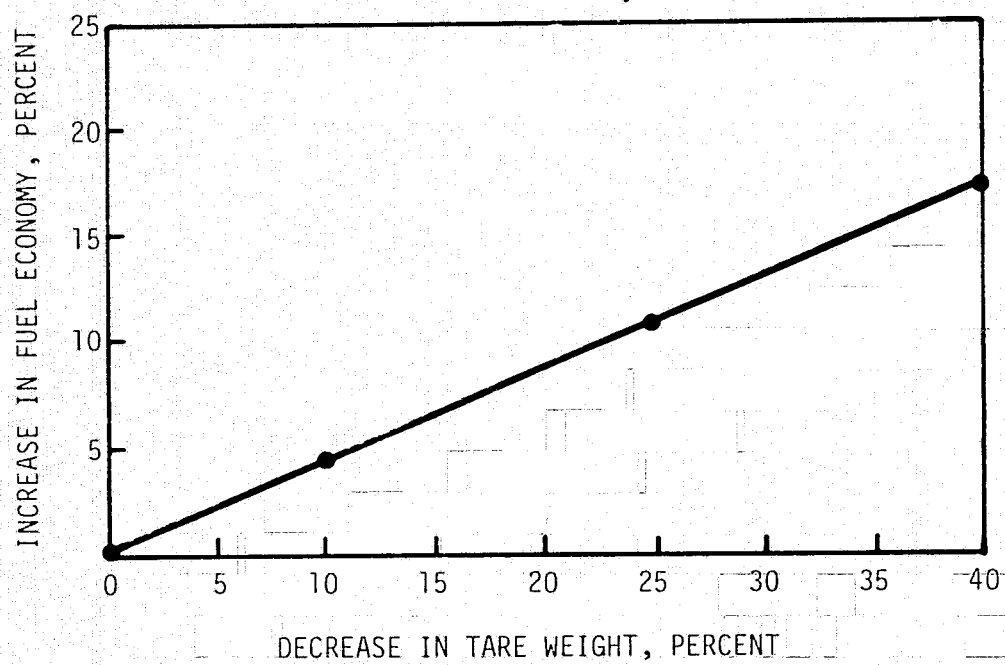
IMPROVEMENT IN AVERAGE TRUCK TON-MILES PER GALLON WITH REDUCED VEHICLE TARE WEIGHT

The improvement in average ton-mile per gallon energy efficiency with reduced vehicle tare weight can be estimated if the average load factor for the truck fleet is known. If a 35 percent decrease in vehicle tare weight is assumed for the use of composite materials in the truck frame, springs, etc., an average 15 percent increase in fuel economy on a ton-mile basis can be expected.

Source:

Arthur D. Little, Inc., "A Study of Technological Improvement to Optimize Truck Configurations for Fuel Economy". NTIS Report Number PB-246-681, September 1975.

IMPROVEMENT IN AVERAGE TRUCK TON-MILES PER GALLON
WITH REDUCED VEHICLE TARE WEIGHT



NEW FREIGHT CARS REQUIRED PER YEAR

The American Railway Car Institute has forecast the need for new freight cars through 1985.

These estimates, by car type, are shown opposite.

These forecasts are based on the following assumptions:

	<u>1975-80</u>	<u>1981-85</u>
Average fleet car capacity (tons)	81.5	87.7
Load factor	80%	
Trips per year	19.2	
Cars retired (thousands)	412	347

The high and low estimates are based on forecasts of tons originated by Class I railroads.

NEW FREIGHT CARS REQUIRED PER YEAR

CAR TYPE	1975-1980 (THOUSANDS)		
	LOW	MID	HIGH
BOX	13.1	15.8	19.3
FLAT	6.7	8.1	9.9
GONDOLA	4.6	5.5	6.7
OPEN HOPPER	15.1	18.2	22.2
CLOSED HOPPER	7.1	8.6	10.5
REFRIGERATOR	2.5	3.0	3.7
TANK	5.0	6.0	7.3
OTHER	<u>.2</u>	<u>.3</u>	<u>.4</u>
TOTAL	54.3	65.5	80.0

CAR TYPE	1981-1985 (THOUSANDS)	
	LOW	HIGH
BOX	14.8	15.3
FLAT	9.0	9.3
GONDOLA	5.5	5.7
OPEN HOPPER	20.6	21.4
CLOSED HOPPER	11.0	11.4
REFRIGERATOR	2.6	2.7
TANK	5.9	6.1
OTHER	<u>.1</u>	<u>.1</u>
TOTAL	69.5	72.0

WEIGHT OF FREIGHT CARS

Rule 88 of the AAR Interchange Rules prescribes total allowable weight of a freight car given the journal size. Combining this data with nominal capacity allows calculation of the light (or tare) weight, as shown in the table opposite.

Each pound saved in light weight translates directly into increased capacity, since total weight is the limiting factor. The percentage capacity increase which can be gained by a reduction in light weight can be calculated from the expression:

$$\left(\frac{\text{Light Weight}}{\text{Nominal Capacity}} \right) \cdot \alpha$$

where α is the percentage reduction in light weight. Consider, for example, a typical new car with capacity 100 tons and light weight of 32 tons. If use of composites is able to reduce the latter by 25 percent, capacity will increase by 8 percent; if use of composites is able to reduce it by 50 percent, capacity will increase by 16 percent.

Average car capacity has increased dramatically in recent years: from a fleet average of 55.4 tons per car in 1960, to 72.8 tons per car in 1974. This will continue to increase as more 100-ton cars are added and older cars are retired. Capacity is expected to increase at a slower rate than previously, however, with total weight on rail limiting capacity to 100 tons per car. Use of composites to reduce light weight provides an alternative to this scenario.

WEIGHT OF FREIGHT CARS
(WEIGHT IN TONS, 4 AXLES PER CAR)

JOURNAL SIZE	TOTAL WEIGHT	NOMINAL CAPACITY	LIGHT WEIGHT
4-1/4 x 8	51.5	30	21.5
5 x 9	71	44	27
5-1/2 x 10	88.5	55	33.5
6 x 11	110	77	33
6-1/2 x 12	131.5	100	31.5
7 x 12	157.5	125	32.5

GRAPHITE COMPOSITE USAGE IN RAILROAD FREIGHT CARS

Because of load handling problems, the most likely graphite composite applications are:

1. Tank cars, whose load is liquid
2. Covered hoppers, whose load is typically grain
3. Box cars.

Typical structural applications include side panels and sections bearing distributed loads.

According to officials of the American Association of Railroads, one car manufacturer is currently developing a tank car with the tank made of a composite material. Factors that inhibit the introduction of composites in railroad freight cars include the large number of manufacturers, the specialty nature of the cars, a lack of research and development, and the fact that stress levels in railroad freight cars are significantly greater than in automotive or aircraft applications. For these reasons, it has been assumed that the introduction of graphite composites in railroad freight cars will not precede the use of graphite composites in the automotive industry.

GRAPHITE COMPOSITE USAGE IN RAILROAD FREIGHT CARS (continued)

In a previous chart, it has been shown that approximately 31,000 box, closed hopper, and tank cars will be manufactured per year in the 1975-1985 time period. It is assumed that this rate of manufacture will continue into the 1990s. Because of the factors that inhibit the introduction of composites in the manufacture of railroad freight cars, it is assumed that only 20 percent of the cars manufactured will use graphite composites. Since a detailed analysis of freight cars has not been completed in this Phase I study, it is assumed that the percentage weight savings achieved in freight cars is the same as that achieved in automobiles, and that the quantity of graphite composites used is proportional to the weight savings. With these assumptions, the total usage of graphite fibers in freight car production is estimated to be approximately 7×10^6 pounds per year.

As in the case of trucks, the reduction in empty weight will be used to increase the load-carrying capacity of the vehicle. Through the use of graphite composites, it is estimated that a 7 percent increase in the nominal capacity of freight cars can be achieved.

GRAPHITE COMPOSITE USAGE IN RAILROAD FREIGHT CARS

- ASSUME USAGE IN 20% OF TANK CARS, CLOSED HOPPERS AND BOX CARS MANUFACTURED AFTER 1990
- ASSUME WEIGHT SAVINGS THE SAME AS THAT ACHIEVED IN AUTOMOBILES (20%)
 - AVERAGE EMPTY WEIGHT DECREASES FROM 30 TONS TO 23 TONS
 - 2100 LBS OF COMPOSITE STRUCTURE PER CAR (AVERAGE)
- TOTAL USAGE OF ABOUT 7×10^6 LBS OF GRAPHITE FIBER PER YEAR
- CAPACITY INCREASE OF 7% IN CARS USING GRAPHITE COMPOSITE CONSTRUCTION

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DEMAND FOR RAIL TRANSIT VEHICLES AND BUSES

The demand for rail transit vehicles and buses is projected by the American Public Transit Association. The estimated number of these vehicles is small compared to the estimated number of automobiles, trucks, and freight cars, and does not appear to be of sufficient magnitude to affect the market for graphite composite materials. If, however, graphite composites are used in passenger automobiles, trucks, and freight cars, it is very likely that they will also be used in these vehicles.

DEMAND FOR RAIL TRANSIT VEHICLES AND BUSES

BUSES

	BUSES/YEAR	
	LOW	HIGH
1975-79	4468	7037
1980-84	4849	5075
1985-89	7762	8109

RAIL TRANSIT VEHICLES

	CARS/YEAR	
	LOW	HIGH
HEAVY RAIL	383	474
LIGHT RAIL	139	147
TROLLEYS	109	159

VEHICLE SAFETY REQUIREMENTS FOR COMPOSITE MATERIALS

The controlled crush of structural members in the vehicle body is known as crash energy management. In contemporary vehicles the crush is controlled by the plastic deformation of the steel structure. Although composite material will not fail plastically, it may be possible to develop composite material structures that can produce suitable crush characteristics by causing the energy-absorbing fractures to occur in a sequential manner, approximating the ideal constant deceleration crash.

In addition to crash energy management, it is necessary that all materials used in the composite, in particular the matrix resins, must meet safety standards on flammability and toxicity. This requirement is being met by non-composite plastics in current vehicle use; it is anticipated that suitable resins will be found to enable the safe use of composite materials in environments where fire is possible.

A significant safety benefit may accrue to the use of composite in the vehicle structure, since their light weight in standard size vehicle bodies could be used to maximize available crush distance for given body weight.

VEHICLE SAFETY REQUIREMENTS FOR COMPOSITE MATERIALS

- COMPOSITES MUST DEMONSTRATE GOOD CRASH ENERGY MANAGEMENT
- MATRIX RESINS MUST MEET FMVSS STANDARDS ON FLAMMABILITY AND TOXICITY

POTENTIAL PAYOFF

- MAXIMUM AVAILABLE CRUSH DISTANCE FOR GIVEN BODY WEIGHT

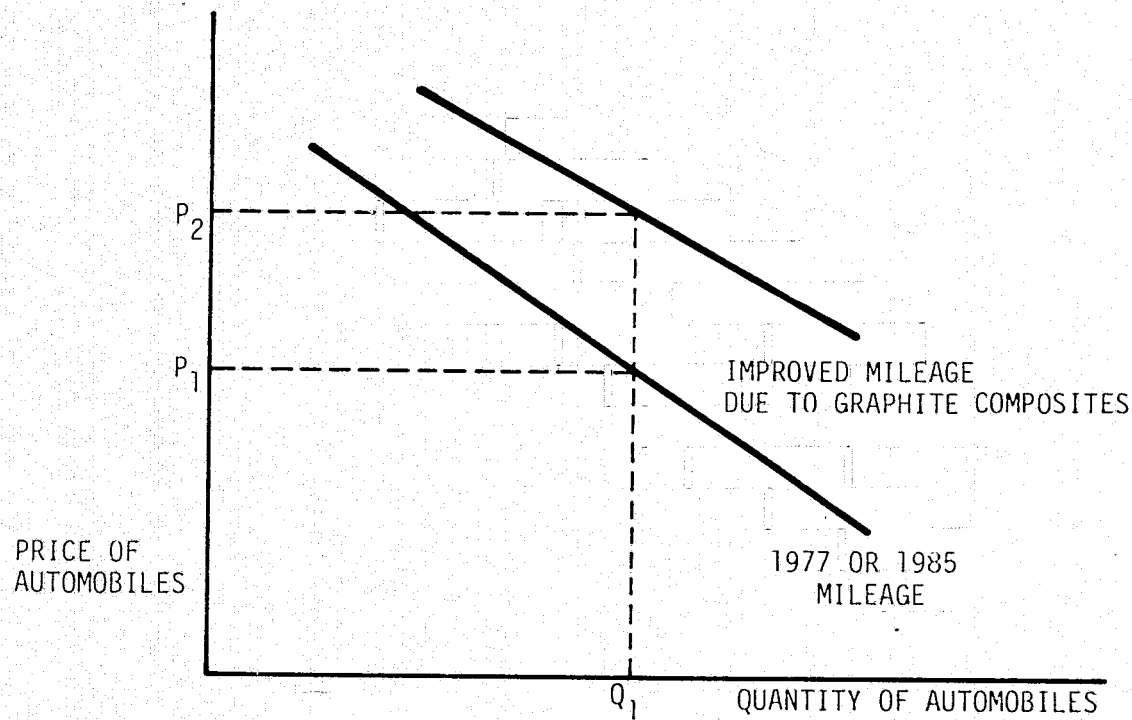
ECONOMIC INCENTIVES FOR THE USE OF COMPOSITES

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INCREASED CONSUMER DEMAND DUE TO IMPROVED AUTOMOBILE FUEL ECONOMY

Initial thoughts were that improvements in fuel economy would raise consumer demand for automobiles. In principle, the "rational" consumer would be willing to pay an additional amount for increased vehicle mileage, an amount approximately equivalent to the present value of gasoline expenditures. Thus, manufacturers could afford to increase the cost per new automobile by as much as $P_2 - P_1$ (see opposite page) in order to achieve fuel economy. Statements by industry officials, however, imply that the costs of increasing fuel economy do not warrant changes, and that consumer demand for fuel economy will not support such improvements. Thus, at the present time the motive for improvements in fuel economy is not economic, but rather legislative, and the standard economic approach shown opposite must be abandoned. This conclusion is, of course, dependent upon the current economic and regulatory environment. Should the price of gasoline, for example, increase significantly, due either to market forces or a gasoline tax, consumer demand for fuel economy could increase sufficiently to provide economic impetus for fuel economy improvements.

INCREASED CONSUMER DEMAND DUE TO IMPROVED AUTOMOBILE FUEL ECONOMY

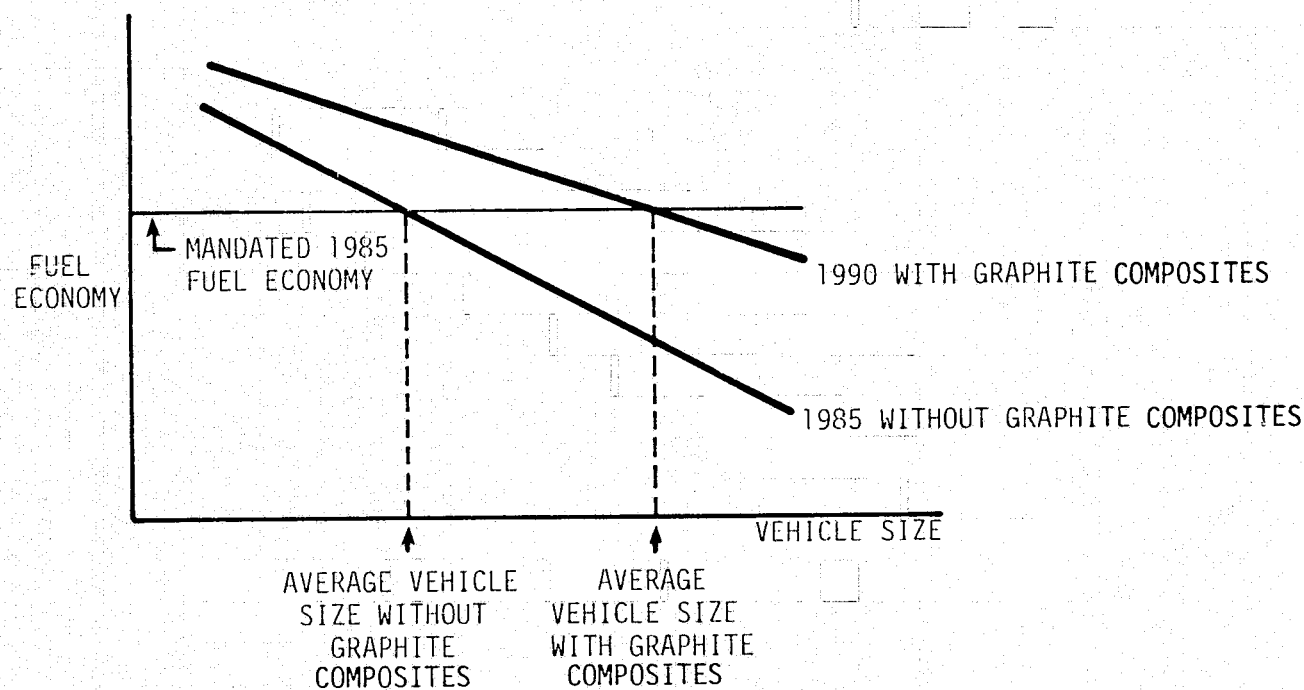
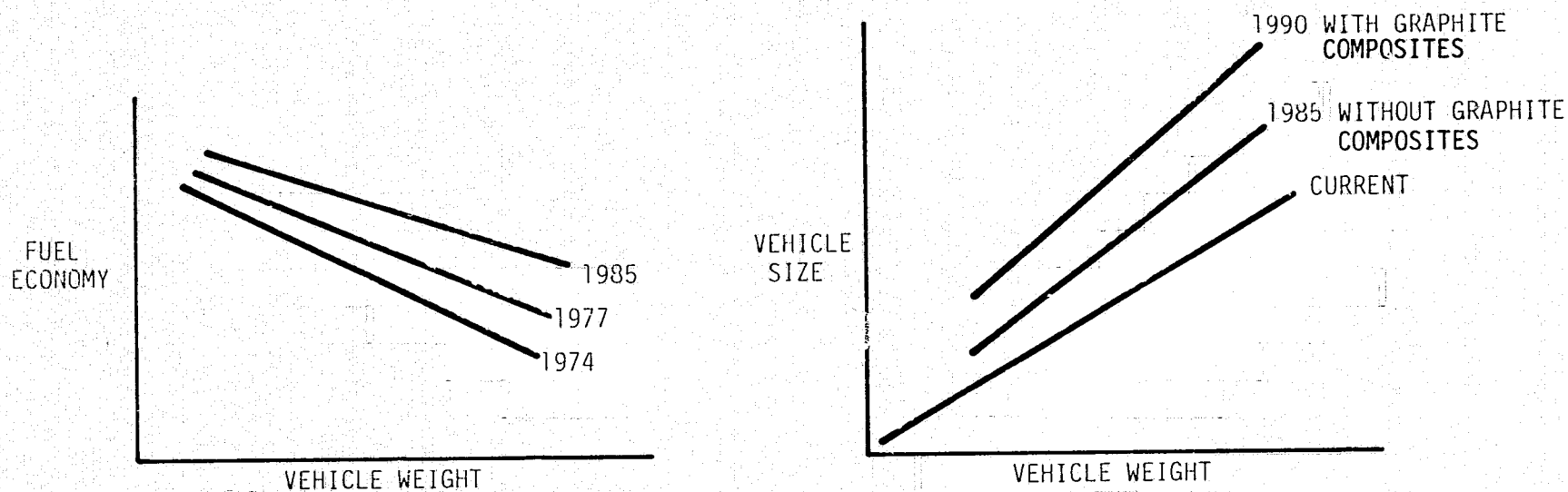


BENEFITS FROM THE INTRODUCTION OF GRAPHITE COMPOSITES INTO AUTOMOBILES

There are still, however, very strong economic incentives in favor of improvements which increase fuel economy. The automotive manufacturers are very concerned about being able to offer a wide mix of vehicle sizes. With current technologies, the average automobile produced in 1985 would have to be subcompact-sized in order to meet 1985 EPA fuel economy standards. Graphite composites can assist in meeting consumer demand for larger vehicles while maintaining good fuel economy. The automobile manufacturers would benefit from increased revenues due to sales of larger cars. It is generally considered that the profit margin is greater on the larger automobile.

The general approach to benefit analysis of composites is shown opposite. Given any state of technology for aerodynamics and engine efficiency, the trade-off between vehicle weight and fuel economy is fixed. These technologies have been, and will continue, to improve, but are fixed at any point in time. Other improvements such as improved design and shifts to lighter materials--plastics, aluminum, composites, etc.--affect the relationship between vehicle weight and vehicle size. In general, the use of lightweight materials, such as composites, permits a larger vehicle with improved fuel economy. It effects a change in the relationship between vehicle size and fuel efficiency, as shown opposite in the bottom figure. Thus, the introduction of composites can be seen to permit a larger average vehicle size under the 1985 fuel economy standards.

BENEFITS FROM THE INTRODUCTION OF GRAPHITE COMPOSITES INTO AUTOMOBILES



AVERAGE 1977 VEHICLE PRICES FOR FOUR SIZE CLASSES

The increased revenue potential from larger automobiles is shown opposite. ECON reviewed the automobile offerings of Chevrolet, Ford and Chrysler-Plymouth. As a proxy for size, the EPA Interior Volume Index is used. "Full-sized" automobiles, before options, fetch more than \$1500 over the "sub-compacts," on average. The classifications are ECON's own and do not completely correspond to those typically used. The cars are classified according to the Interior Volume Index as follows:

FULL-SIZED (≥ 100)

Ford LTD
Chrysler Newport
Chevrolet Impala

INTERMEDIATE (90-99)

Ford Granada
Plymouth Volare
Plymouth Fury
Mercury Cougar
Chevrolet Monte Carlo
Chevrolet Nova

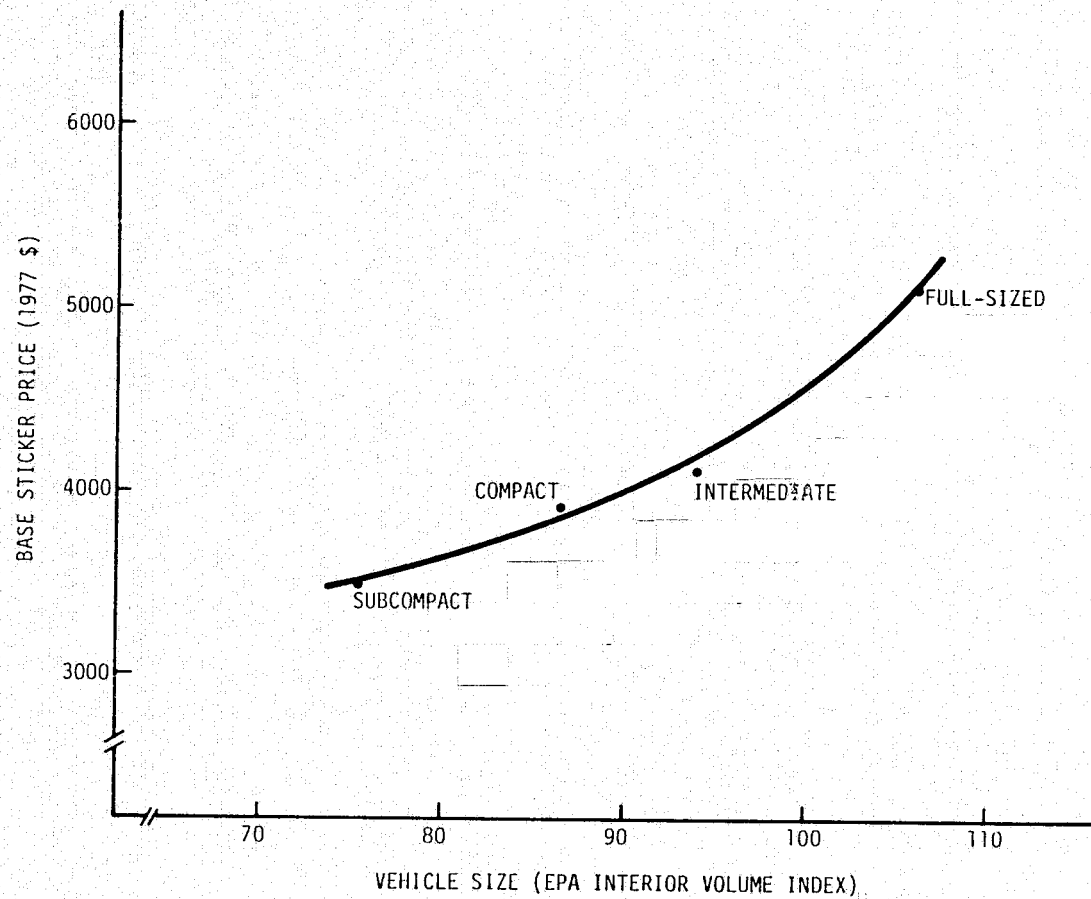
COMPACT (81-89)

Ford Maverick
Chevrolet Camaro
(Volkswagon Dasher)

SUBCOMPACT (≤ 80)

Ford Mustang II
Ford Pinto
Plymouth Arrow
Chevrolet Vega
Chevrolet Chevette

AVERAGE 1977 VEHICLE PRICES AND SIZES FOR FOUR SIZE CLASSES



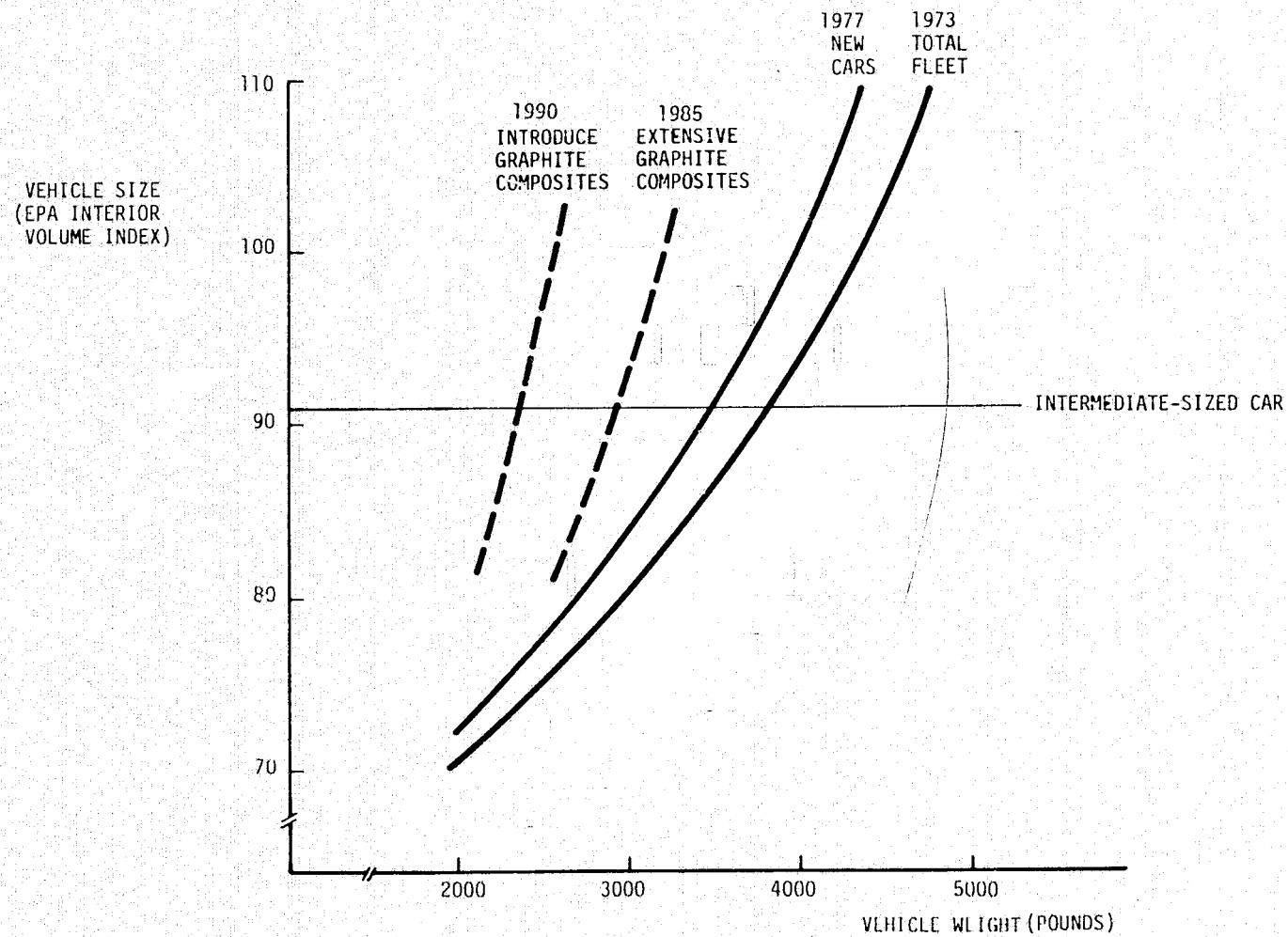
TRADE-OFF BETWEEN VEHICLE WEIGHT AND SIZE

The figure opposite shows the technological trade-off between vehicle weight and size for three points in time. The average vehicle weight for GM cars in 1977 is 4200 pounds. This weight is expected to decrease using only minimal amounts of composites, to 3100 pounds by 1985. A greater use of composites could permit a still lighter car.

Sources

1973 Fleet:	McGillivray, Urban Institute
1985 GM Estimate:	GM Letter to NHTSA

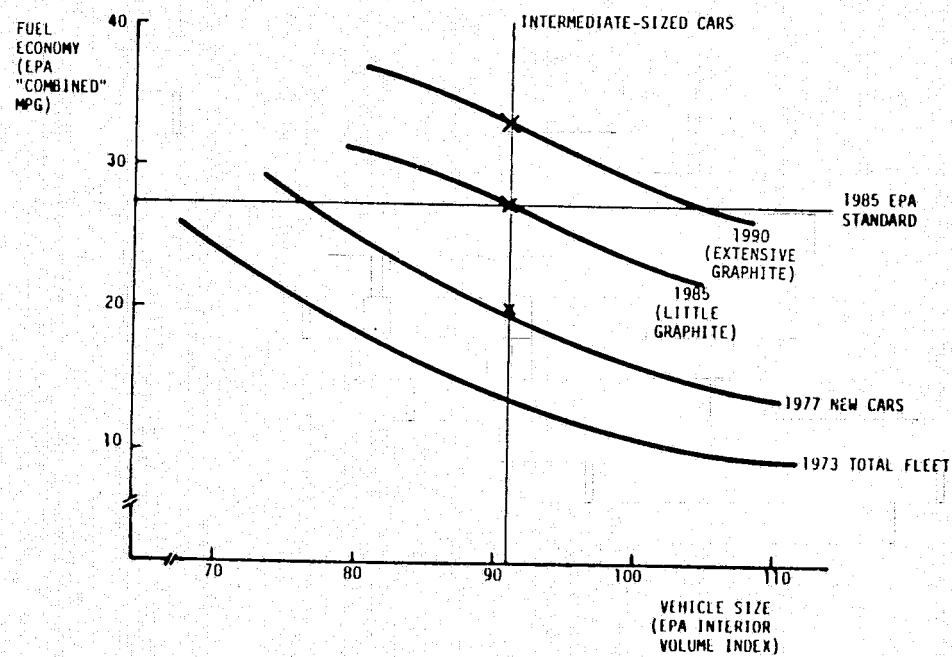
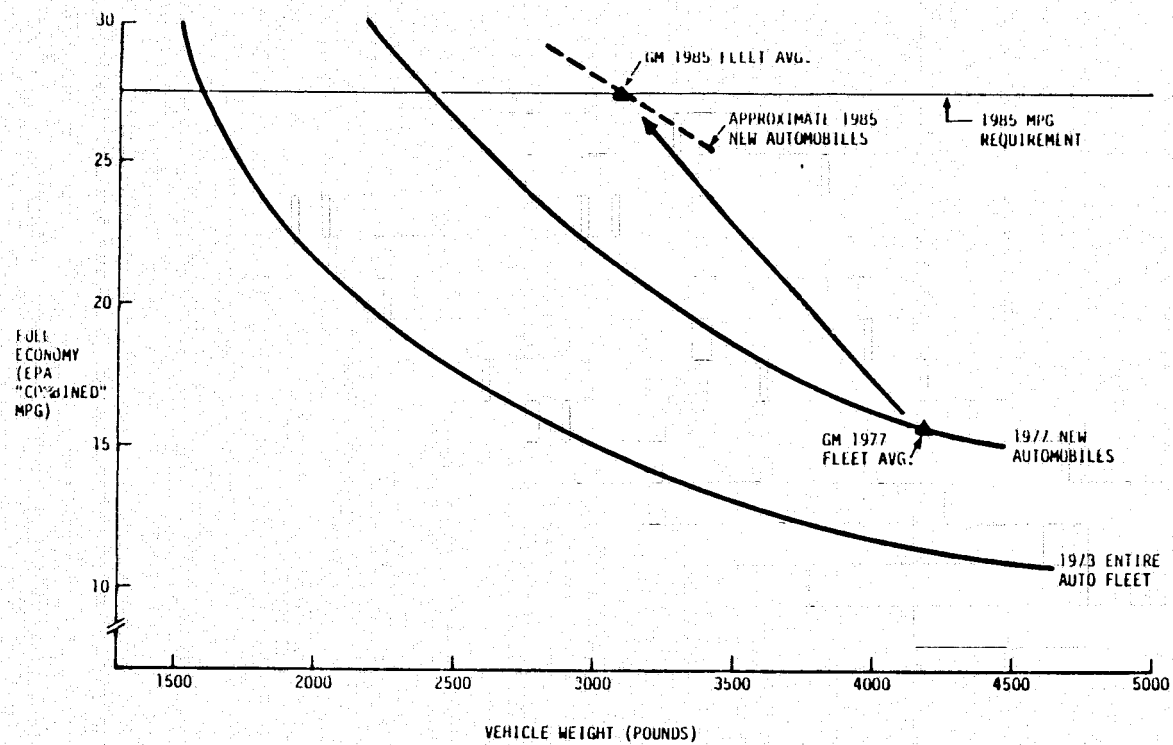
TRADE-OFF BETWEEN VEHICLE WEIGHT AND SIZE



TECHNOLOGICAL TRADE-OFFS

The figures opposite illustrate the existing and future technological changes in automobile manufacturing. The trade-off between weight and size has already been improved since 1973. Under legislative pressure, the trade-off will be further improved so as to produce an intermediate-sized automobile at approximately 3000 pounds, versus approximately 4000 pounds today. With a maximum use of graphite composites, ECON estimates that this size car could be further reduced to less than 2400 pounds.

Fuel economy improvements relative to vehicle size are shown in the figure on the bottom. The average 1985 automobile is seen to have an interior size index of 91 (intermediate-sized) while achieving the EPA standard of 27.5 MPG. Extensive use of graphite composites could permit the same size automobile to achieve 31-36 MPG. If desired, the average fleet size could be raised to that of a full-sized automobile while meeting the EPA 1985 MPG standard.



TECHNOLOGICAL TRADEOFFS

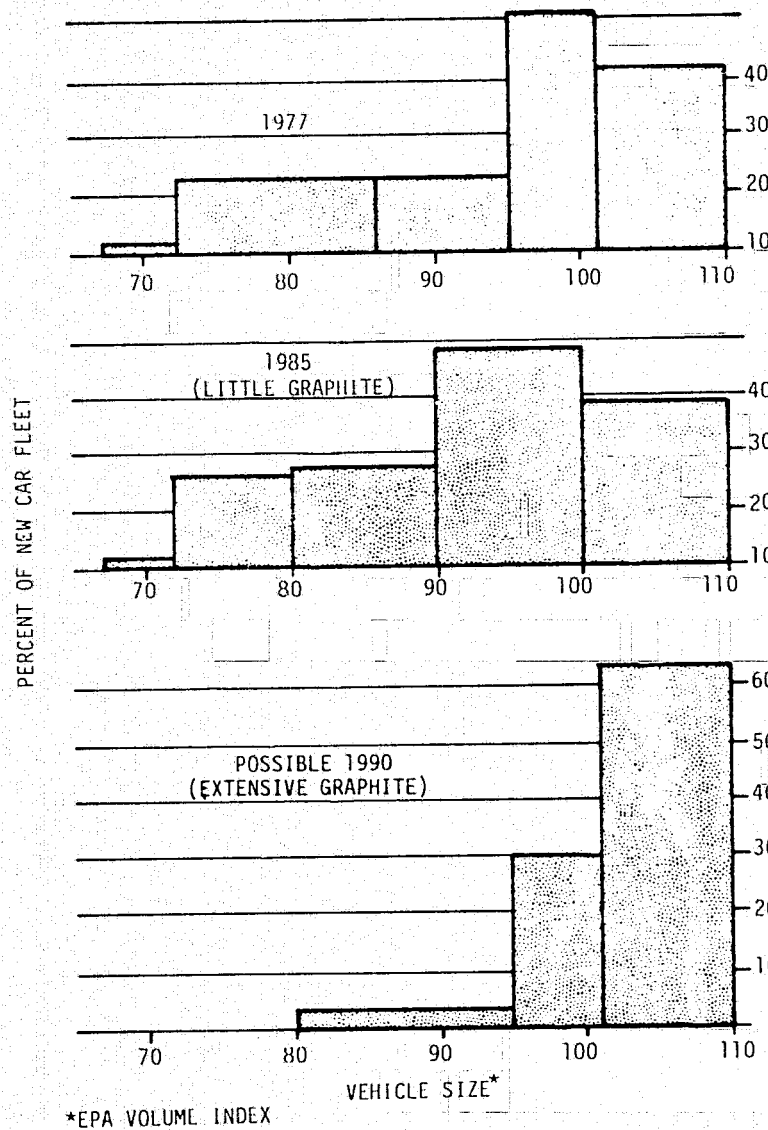
FLEET SIZE DISTRIBUTIONS

The opposite figures show the estimated fleet size distributions for the years 1977, 1985, and 1990. An expected slight shift to smaller cars is anticipated in 1985. The 1990 scenario was developed simply to show the largest possible average vehicle size for the fleet while satisfying EPA's mileage requirement, assuming extensive use of graphite composites. This is not a prediction of what the fleet would look like; it merely conveys the amount of flexibility permitted by the introduction of composites. Using 1977 base sticker prices for the different size classes, annual revenues from new car sales were forecasted. No price increases due to mileage and other (emissions, safety,...) requirements were estimated. Revenues are shown to grow due to increased car sales. The increased revenues for the year 1990 attributed to the changes in size class distribution from that of 1985 (middle figure) to the largest possible average vehicle size distribution (bottom figure) is \$12.9 billion. It is not likely that consumers will demand this type of fleet mix, so some other changes are possible.

Sources

Auto Sales Forecasts:	Rand Corporation
1977 & 1985 New Car Mix:	GM Letter to NHTSA

FLEET SIZE DISTRIBUTIONS



APPROXIMATE REVENUES
FROM 1977 BASE
STICKER PRICE

1977: \$56.3 B

1985: \$70.8 Billions

1990 (EXTENSIVE GRAPHITE) \$93.9 Billions

1990 (LITTLE GRAPHITE) \$81.0 Billions

DIFFERENCE \$12.9 Billions

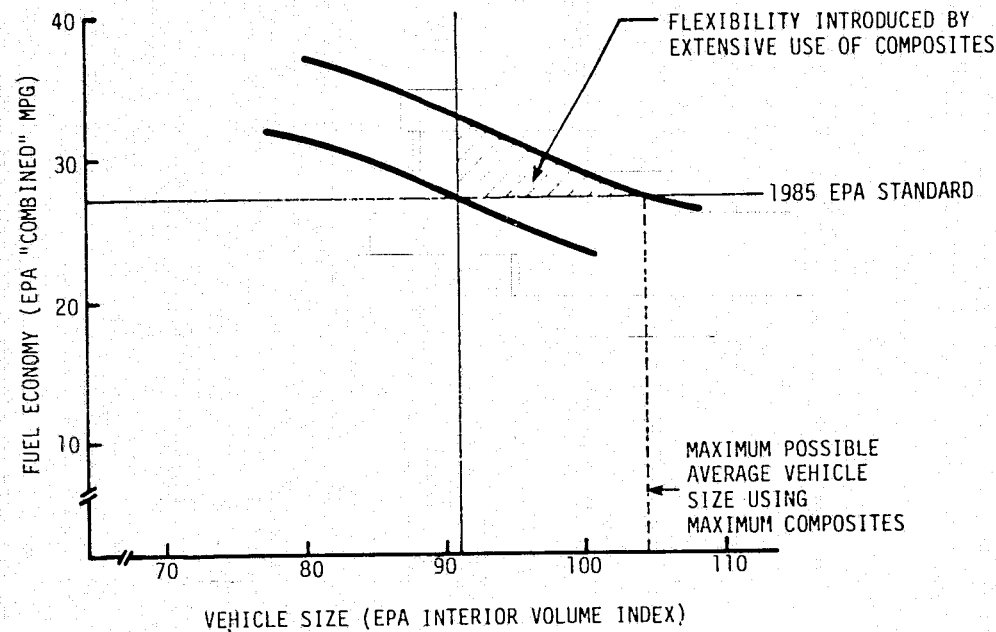
OPTIONS INTRODUCED BY EXTENSIVE USE OF COMPOSITES

Since it is unlikely that 65 percent of the 1990 fleet will be composed of full-sized automobiles, flexibility in other areas is possible. The average vehicle size for the fleet may increase back to 1977 levels, but even greater fuel economy could be mandated by EPA; emission standards could also be tightened. The intermediate-sized vehicle, with extensive graphite composites use, could easily achieve as much as 32 MPG. If this was mandated as the new car fleet average, an annual gasoline saving of 0.7 billion gallons would result, a decrease from 53.3 to 52.6 billion gallons per year. This calculation is strictly of savings for the new cars introduced in 1990; once the entire fleet achieves this standard, the fuel savings would be at least 6.8 billion gallons, a decrease from 48.9 to 42.1 billion gallons per year. Manufacturers may decide to forego some of the other more expensive or less desirable technical changes: for example, diesel penetration could diminish. A final option is that the manufacturer could offer a more desirable product to the consumer. He may be able to lower the price somewhat or improve other characteristics.

Source

1990 Vehicle Miles Traveled by New Cars: Rand Corporation

OPTIONS INTRODUCED BY EXTENSIVE USE OF COMPOSITES



- INCREASE AVERAGE VEHICLE SIZE FOR NEW CAR FLEET (SEE PREVIOUS SLIDE)
- STRICTER EPA MILEAGE/EMISSION REQUIREMENTS WHILE MAINTAINING FLEET SIZE
E.G. INCREASE MILEAGE REQUIREMENT TO ~32 MPG, YIELDS
FUEL SAVINGS OF 0.7 BILLION GALLONS OF GASOLINE PER YEAR
INCREASING TO ~6.8 BILLION GALLONS.
- DECREASED DEPENDENCE ON MORE EXPENSIVE FUEL EFFICIENCY TECHNOLOGIES
- MORE DESIRABLE PRODUCT -- PRICE, PERFORMANCE, HANDLING AND RIDE, ETC.

TASKS TO BE DONE--USE OF GRAPHITE COMPOSITES IN AUTOMOBILES

It has been demonstrated that the use of graphite composites could introduce considerable flexibility into meeting the EPA requirements. Exactly how the resulting automobiles mix will be affected, cannot yet be predicted. This would be determined by economic incentives not yet studied. The ultimate use of graphite composites will depend upon their cost-effectiveness compared with other fuel-efficiency technologies. Their use will also depend upon consumer preferences and the regulatory and economic situation in the years to come. These relationships could be estimated and a model developed which estimates the most economic use of graphite composites, the type of automobile which will be produced and the resulting fuel savings. These results would be a function of the regulatory environment and, thus, changes in the mileage requirement, for example, could be examined.

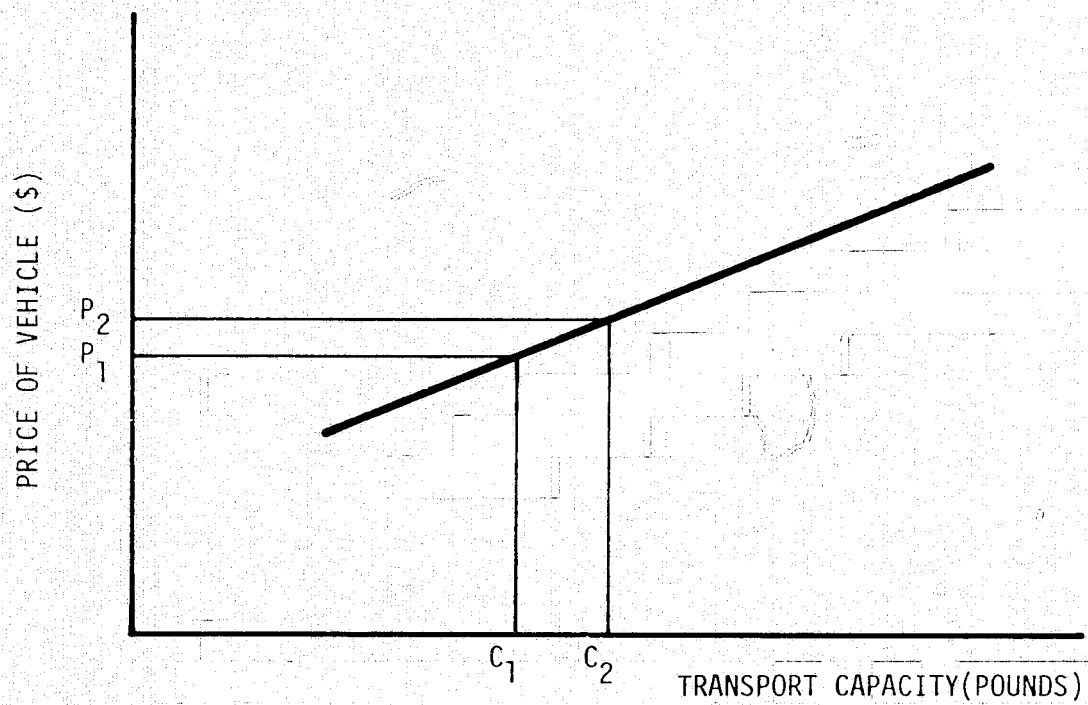
TASKS TO BE DONE--USE OF GRAPHITE COMPOSITES IN AUTOMOBILES

- COMPARE THE COST EFFECTIVENESS OF COMPOSITES VS. OTHER TECHNOLOGIES IN ACHIEVING EPA STANDARD
- COMPARE CONSUMER PREFERENCES FOR MILEAGE, AUTO PRICE, SIZE AND LUXURY, PERFORMANCE AND HANDLING
- DEVELOP MODEL TO ESTIMATE THE OPTIMAL USE OF COMPOSITES AND THE TYPE OF AUTOMOBILE THAT RESULTS
- INVESTIGATE HOW CHANGES IN EPA REQUIREMENTS AFFECT USE OF COMPOSITES AND RESULTING AUTOMOBILE TYPE

BENEFIT ANALYSIS OF COMPOSITES IN OTHER LAND-BASED VEHICLES

The purpose of land vehicles other than automobiles: pickup and long-haul truck, railroad cars, is usually to carry freight. The introduction of composites into these vehicles permits a decrease in the gross weight of the carrier and thus an increase in the vehicle's transport capacity. Typically, manufacturers can charge more for vehicles with greater capacity. Thus, there is incentive to introduce composites to increase the transport capacity of freight vehicles. The increased price (opposite figure) must be traded off against the greater costs involved in the use of composites.

BENEFIT ANALYSIS OF COMPOSITES IN OTHER LAND BASED VEHICLES



NATIONAL ECONOMIC IMPACT

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NATIONAL ECONOMIC IMPACT OF COMPOSITES

Method of Analysis

The economic impact of the materials substitution is dependent on both the magnitude and rate of substitution over time. The results of ECON's work on the composition of the average 1985 and 1990 automobile indicated the various percent changes in the weight of glass, ferrous metals, nonferrous metals and plastics used, all relative to a 1971 base year.

An input-output analysis was used to give rough order of magnitude estimates of the national economic impact, since the primary, secondary and tertiary impacts of a change in technology of producing a given good can be analyzed in some detail using this technique. The method allows computation of changes in output resulting in the technological change from which changes in employment can be inferred.

NATIONAL ECONOMIC IMPACT OF COMPOSITES

METHOD OF ANALYSIS

- A MACRO AND SECTOR BY SECTOR ASSESSMENT OF THE IMPACT OF SUBSTITUTING PLASTICS, COMPOSITES AND NONFERROUS METALS FOR IRON AND STEEL, IN DOMESTIC AUTO MANUFACTURING.
- METHOD OF ESTIMATION IS STANDARD INPUT-OUTPUT ANALYSIS.
- THE MACROECONOMIC INDICATORS ARE GROSS NATIONAL PRODUCT (GNP) AND NATIONAL LEVEL OF EMPLOYMENT.
- THE SECTOR INDICATORS ARE OUTPUT AND EMPLOYMENT WITH PARTICULAR EMPHASIS ON THE FOLLOWING SECTORS:
 - MOTOR VEHICLE ASSEMBLY
 - COMPONENT SUPPLIERS TO AUTO MANUFACTURING
 - RAW MATERIAL SUPPLIERS DEPENDENT ON AUTO MANUFACTURING.
- ALL RESULTS ARE ROUGH ORDER OF MAGNITUDE ESTIMATES.

INTRODUCTION TO INPUT-OUTPUT ANALYSIS

The rationale for term input-output analysis is clear. The output of any industry (say the steel industry) is needed as an input in many other industries, or even for that industry itself; therefore, the "correct" level of steel output will depend on the input requirements of all the n industries. In turn, the output of many other industries will enter into the steel industry as inputs, and consequently the "correct" levels of other products will in turn depend partly upon the input requirements of the steel industry. In view of this interindustry dependence, any set of "correct" output levels for the n industries must be one that is consistent with all input requirements in the economy, so that no bottle-necks will arise anywhere.

The solution of an input-output system begins with the organization of the economy into distinct industries, and the computation of the dollar flows between all sectors. The units of the flows must be in dollars since aggregations of physical units, say 15 tons of steel plus 3 yards of fabric, have no meaning. Computation of the dollar flows is not a simple task either, due to the need for reliable price indices for each sector.

INTRODUCTION TO INPUT-OUTPUT ANALYSIS

- THE ESSENTIAL QUESTION THE METHOD ATTEMPTS TO ANSWER IS: WHAT LEVEL OF OUTPUT SHOULD EACH OF THE n INDUSTRIES IN AN ECONOMY PRODUCE, IN ORDER TO JUST SATISFY THE FINAL CONSUMER DEMAND FOR EACH OF THE n PRODUCTS?
- THE ANSWER IS FOUND BY FIRST ORGANIZING THE ECONOMY INTO CAREFULLY DEFINED INDUSTRIES AND DETERMINING WHAT THE DOLLAR FLOWS ARE BETWEEN EACH AND EVERY INDUSTRY, THE LABOR SECTOR AND FINAL DEMAND.

EXAMPLE OF INPUT/OUTPUT TABLE

Having computed the dollar flows, the presentation of the data in a transactions table is a useful exercise. Reading along the rows gives distribution of output; the columns indicate the inputs required. The agricultural sector, for example, distributes its output by keeping \$300 worth of its products, sending \$400 worth to the manufacturing sector, and selling \$300 worth to the consumers. It requires \$500 of labor, \$200 of manufactured goods and the \$300 it kept in the first place.

The direct technological coefficients are computed by simply dividing the value of each input to a particular industry by that industry's total output. These coefficients are direct (as opposed to indirect) since they do not reflect secondary demand impacts on other sectors. The input column totals must always add to unity.

EXAMPLE OF INPUT/OUTPUT TABLE

INDUSTRIES	INPUTS TO AGRICULTURE	INPUTS TO MANUFACTURING	FINAL DEMAND	TOTAL OUTPUT
AGRICULTURE	300 .3	400 .2	300	1,000
MANUFACTURING	200 .2	800 .4	1,000	2,000
LABOR SERVICES	500 .5	800 .4	0	1,100

COEFFICIENT TOTAL: 1.00 1.00

- TO MAKE \$1.00 OF A MANUFACTURED GOOD, IT TAKES 20¢ OF AGRICULTURAL GOODS, 40¢ OF OWN INPUT AND 40¢ OF LABOR SERVICES.
- ALL FLOWS ARE IN DOLLAR UNITS.

THE ALGEBRA OF INPUT/OUTPUT ANALYSIS

The equations simply re-express the table in a more useful computational form. The output of the n^{th} industry x_n is distributed to industries x_1 through x_n in a manner which is proportional to each x_j industry output. The coefficients a_{ij} correspond to the decimal values found in the table.

There are several interesting attributes of the coefficients a_{ij} , if the system makes any economic sense; 1) each a_{ij} must be less than unity, otherwise the system would imply, for example, that it takes \$7.20 of iron ore to make \$1.00 of steel; 2) the a_{ij} must all be positive for if industry 1 transferred goods to industry 2, this would be classified as an input to industry 2, not a negative flow from 2 to 1.

The matrix $[I - A]$ is, of course, square (in x_n industries) and conformable with both vectors x and d .

THE ALGEBRA OF INPUT/OUTPUT ANALYSIS

- EACH INDUSTRY PRODUCES AN OUTPUT SUFFICIENT TO MEET ITS OWN REQUIREMENTS, OTHER INDUSTRY REQUIREMENTS AND FINAL CONSUMER DEMAND.

$$\begin{aligned} x_1 &= a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n + d_1 \\ &\vdots \\ x_n &= a_{n1}x_1 + a_{n2}x_2 + \dots + a_{nn}x_n + d_n \end{aligned}$$

- REWRITING:

$$\begin{aligned} (1-a_{11})x_1 - a_{12}x_2 - \dots - a_{1n}x_n &= d_1 \\ -a_{21}x_1 + (1-a_{22})x_2 - \dots - a_{2n}x_n &= d_2 \\ &\vdots \\ -a_{n1}x_1 - a_{n2}x_2 - \dots + (1-a_{nn})x_n &= d_n \end{aligned}$$

a_{ij} = DIRECT TECHNICAL COEFFICIENT

x_n = OUTPUT OF n^{th} INDUSTRY

d_n = FINAL DEMAND FOR GOODS OF n^{th} INDUSTRY

- OR IN MATRIX NOTATION: $(I - A)x = d.$

SOLUTION OF INPUT/OUTPUT SYSTEM

The solution of the general system is simple in theory but not in practice. Computation of $(I - A)^{-1}$ for large matrices such as 367 by 367 tax even the largest computer. The problem is not in developing an efficient inversion routine but rather in the nature of $(I - A)$ in practice. Problems such as finding the determinant equal to machine zero due to near-extreme multicollinearity are not uncommon. As a result, approximation techniques are in wide use.

It is useful now to list the caveats that always accompany static input/output analysis. The assumptions are very restrictive but the end result is a powerful technique that can give order of magnitude estimates more easily and dependably than any econometric method, or back of the envelope calculations. These are: 1) each industry produces only one homogeneous commodity (this does permit the case of two or more jointly produced commodities, if produced in fixed proportion); 2) each industry uses a fixed input ratio for the production of its output; 3) production in every industry is subject to constant returns to scale, so that a k -fold change in every input will result in exactly a k -fold change in output.

SOLUTION OF INPUT/OUTPUT SYSTEM

- SO FAR ONLY THE DIRECT REQUIREMENTS OF EACH INDUSTRY FOR EVERY INDUSTRY'S OUTPUT HAS BEEN COMPUTED, I.E., THE DECIMALS FOUND IN THE TABLE OR THE INDIVIDUAL a_{ij} .
- IN ORDER TO FIND THE GENERAL SOLUTION TO THE SYSTEM (THE OUTPUT REQUIRED TO JUST MEET THE FINAL DEMAND) THE MATRIX EQUATION:

$$(I - A)x = d$$

IS SOLVED FOR x , THE FINAL OUTPUT VECTOR, OR:

$$x = (I - A)^{-1}d.$$

- THE COEFFICIENTS OF $(I - A)^{-1}$ INDICATE NOT ONLY THE PRIMARY DEPENDENCIES WITHIN THE ECONOMY BUT ALSO THE SECONDARY, TERTIARY AND n^{th} DEPENDENCIES.
- FOR EXAMPLE, AUTOMOBILES ARE MADE OF STEEL; STEEL REQUIRES ENERGY, IRON ORE; IRON ORE REQUIRES HEAVY MINING MACHINERY AND SO FORTH.

BUREAU OF ECONOMIC ANALYSIS (BEA) I/O TABLES

The BEA 1971 85 industry table was used in the analysis. Though the table represents the economy as it was in 1971, it is the most recent table available and was released in March 1977. The BEA tables are computed using data from the national income accounts and census bureau data. The advantage of the larger tables (365, 485 industry level) is their greater detail and some avoidance of the aggregation problem. As stated before, the I/O technique assumes a homogeneous output for each industry. Greater detail lends credence to the use of the homogeneity assumption.

BUREAU OF ECONOMIC ANALYSIS (BEA) I/O TABLES

- BEA CURRENTLY ESTIMATES THREE TABLES OF VARYING DETAIL FOR THE NATIONAL ECONOMY: 85 INDUSTRY LEVEL, 365 INDUSTRY LEVEL AND 485 INDUSTRY LEVEL.
- ECON'S RESULTS ARE BASED ON THE 85 INDUSTRY 1971 TABLE. THE PARTICULAR VERSION USED IS THE MOST RECENT AND WAS RELEASED IN MARCH 1977. THE LARGER TABLES ARE UPDATED LESS FREQUENTLY.

DETAILED METHODOLOGY

The "technology" of a manufacturing process for a given industry is altered by changing the direct coefficients in the input column of the relevant industry. For example, for industry number 5, each a_{i5} would be changed to reflect the new proportions. The impact of the change would be computed by estimating a new inverse $(I - A^*)^{-1}$ and then finding X , or the new output vector by $(I - A^*)^{-1} d = X$.

It is conceivable that the final (consumer) demand vector could change as a result of the process change. It is almost certain that the final demand vector d will change over time and that by 1985 it will bear no resemblance to 1971. Because the level of confidence that can be placed on any estimate of final demand 8 or 13 years into the future is quite low, it may be better to assume that all final demands grow at a level proportional to national income. This assumption seems more plausible than a guess.

It is also true that the elements of $(I - A)^{-1}$ will change over time in addition to the projected changes made in this study. These coefficients will change less rapidly than the final demand values. Fortunately we have a measure of what the year end will be based on past BEA experience. BEA calculated that from the period 1967-1971, based on the actual values for both years, the inverse coefficient error rate was about 2 percent a year. Thus, we can infer that the 1971 table could be 28 percent off by 1985 and 38 percent in error by 1990.

DETAILED METHODOLOGY

- IDEALLY TO EVALUATE THE IMPACT OF COMPOSITES, THE DIRECT a_{ij} COEFFICIENTS WOULD BE CHANGED TO REFLECT THE CHANGE IN THE MANUFACTURING TECHNOLOGY OF AUTOMOBILES AND THEN A NEW INVERSE $(I - A)^{-1}$ WOULD BE COMPUTED.
- THE PRODUCT OF $(I - A)^{-1}$ AND AN ESTIMATED 1985, 1990 FINAL DEMAND VECTOR WOULD GIVE THE OUTPUT BY INDUSTRY REQUIRED TO EFFECT THE CHANGE.
- A COMPARISON OF THE CHANGE IN OUTPUT LEVELS BY INDUSTRY USING THE OLD AND THEN THE NEW INVERSE WOULD INDICATE THE SECTOR AND MACRO IMPACTS.
- FOR TODAY'S PRESENTATION, A NEW INVERSE OF THE ENTIRE COEFFICIENT MATRIX WAS NOT COMPUTED EXACTLY. INSTEAD A PSEUDO INVERSE WAS CALCULATED BY ALTERING THE COEFFICIENTS OF ONLY THE FOLLOWING SECTORS:
 - FERROUS METAL
 - NONFERROUS METAL
 - PLASTICS (FIBERS)
 - GLASS
 - BROAD AND NARROW FABRICS, YARD THREAD MILLS (WEAVERS OF FIBERS).
- EMPLOYMENT WAS CALCULATED BY ASSUMING IT A CONSTANT FUNCTION OF OUTPUT.

ESTIMATED IMPACTS 1985, 1990

The most dramatic impacts of car redesign were found in those sectors which are the primary suppliers of commodities to the automobile industry. The annual growth rate or contraction rate for both the primary and secondary suppliers is found in the first columns. It should be noted that the 85 by 85 I/O table is probably too insensitive a tool to evaluate the impact of composites by itself. What is shown is the impact of the substitution of nonferrous metals, plastics and composites for iron and steel. The change in composites was accounted for by altering the coefficients in the plastics (fiber) sector and fabric weaving sectors.

For a comparison of how these annual growth and contraction rates compare with the normal course of these sectors, the Bureau of Labor Estimates are shown in the second column. The annual employment change due to the entire substitution is given in the right hand columns. The annual employment change was found by using 1971 BLS employment statistics in each sector and applying the annual percentage change found in the left hand column. Thus, employment is assumed to be a constant function of output as measured in 1971 dollars. The change in GNP, resulting from the use of composites, is projected to be less than one-tenth of one percent.

This analysis indicates that significant economic effects can be anticipated within specific sectors of the economy as a result of the use of graphite composites in surface transportation, the overall effect of the use of graphite composites on employment and GNP will probably be insignificant.

ESTIMATED IMPACTS 1985, 1990

I/O NO.		ANNUAL GROWTH OR CONTRACTION DUE TO SUBSTITUTION (%)		BLS ANNUAL PROJECTED GROWTH (%)		ANNUAL EMPLOYMENT CHANGE DUE TO SUBSTITUTION	
		1985	1990	1985	1990	1985	1990
	<u>PRIMARY SUPPLIERS</u>						
28	PLASTICS AND SYNTHETIC MATERIALS	+ .6	+ .6	+ .2	.2	1000	1000
35	GLASS AND GLASS PRODUCTS	- .5	- .5	.9	.9	- 900	- 900
37	PRIMARY IRON AND STEEL MANUFACTURING	- .7	- .8	- .5	- .5	-6000	-6500
38	PRIMARY NONFERROUS METALS MANUFACTURING	+1.2	+1.3	.5	.5	1000	2500
32	RUBBER AND MISCELLANEOUS PLASTICS	- .3	- .3	.7	.7	- 500	- 500
	<u>SECONDARY SUPPLIERS</u>						
5	IRON AND FERROALLOY ORES MINING	- .2	- .2	-1.5	-1.5	- 100	- 100
6	NONFERROUS METAL ORES MINING	.2	.2	2.3	2.3	100	100
7	COAL MINING	--	--	--	--	--	--
8	BROAD AND NARROW FABRICS, YARN THREAD MILLS	.1	.1	- .4	- .4	500	500
9	MISCELLANEOUS TEXTILE GOODS & FLOOR COVERINGS	--	--	--	--	--	--
10	CHEMICALS AND SELECTED CHEMICAL PRODUCTS	.1	.1	.2	.2	400	400
41	SCREW MACHINE PRODUCTS, BOLTS, NUTS, ETC.	--	--	2.1	2.1	--	--
42	OTHER FABRICATED METAL PRODUCTS	--	--	1.5	1.5	--	--
47	METAL WORKING MACHINERY	--	--	.7	.7	--	--
	EMPLOYMENT TOTAL					-4500	-3500

ENERGY IMPACT OF COMPOSITES IN THE MANUFACTURING OF AUTOMOBILES

The source of the steel KWH usage per ton was from an article by Berry and Fels,^{*} which estimated the energy used at each step in the production of one automobile. The KWH figures for steel includes only the energy used in the steel furnace, not the mining costs and other indirect energy consumption. The KWH figure for graphite composites was based on an interview with a Union Carbide executive.

^{*} Science and Public Affairs, R. Stephen Barry, Margaret F. Fels, "The Energy Cost of Automobiles," December 1973.

ENERGY IMPACT OF COMPOSITES IN THE MANUFACTURE OF AUTOMOBILES

- IF 90 POUNDS OF COMPOSITES ARE USED TO REPLACE 180 POUNDS OF STEEL, 62 KWH PER AUTOMOBILE ARE SAVED.
- IF BY 1990, 19 MILLION CARS A YEAR ARE PRODUCED, THE ENERGY SAVINGS ARE $1.173 \cdot 10^9$ KWH ANNUALLY. AT 6 CENTS A KILOWATT HOUR, THIS TRANSLATES TO A SAVINGS OF ABOUT 7 MILLION DOLLARS A YEAR IN UNDISCOUNTED 1977 DOLLARS.
- THE ENERGY CONSUMPTION WAS TAKEN TO BE 1,375 KWH PER TON FOR BOTH GRAPHITE AND FINISHED STEEL.

APPENDIX A

Physical Properties of Advanced Composites

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FIBER PROPERTIES

The mechanical properties of the fibers are determined by the conventional twisted yarn test (aramid fiber) or by the resin impregnated strand test. Slightly higher values are achieved using the second type of test since the treatment of the fiber's surface (for example, by sulanylazidosilanes if epoxies are used as resins) increases the interlaminar shear strength when the fiber is used in a resin matrix composite and also prevents a decoupling at the interface which could result in low fatigue resistance.

It is readily observed that the tensile strength of aramid, graphic and glass fibers is comparable or better than those of steel or aluminum and that the graphite fibers also have higher stiffness (expressed by tensile moduli). The specific weights of fibers are much lower than those of steel; the aramid fibers are the lightest.

When the fibers are combined with resins, their specific strengths and moduli are somewhat lower than when tested alone since the strengths and moduli of resins are much lower than those of fibers.

FIBER PROPERTIES					
Material	Fiber	Tensile Strength (psi)	Tensile Modulus 10 ⁶ (psi)	Density (lb/in ³)	Elongation to Break (%)
Aramid	Kevlar 49	430,000	19	0.053	2.3
Graphite	Thornel P**	175,000	55	0.072	0.3
	Thornel 300**	385,000	33	0.063	1.4
	AS3+	400,000	32	0.064	N.A.
	HTS+	400,000	34-37	0.063	N.A.
Glass	E-Glass*	350,000	10	0.092	3.5
Steel	Stainless Steel	250,000	29	0.284	2.0
Aluminum	Aluminum	80,000	10	0.1	N.A.
<p>* Unimpregnated yarn tests--ASTM2256-66 (Source: DuPont)</p> <p>** Resin impregnated strand test--ASTMD2343-67 (Source: Union Carbide)</p> <p>+ Resin impregnated strand test--ASTMD2343-67 (Source: Hercules)</p>					

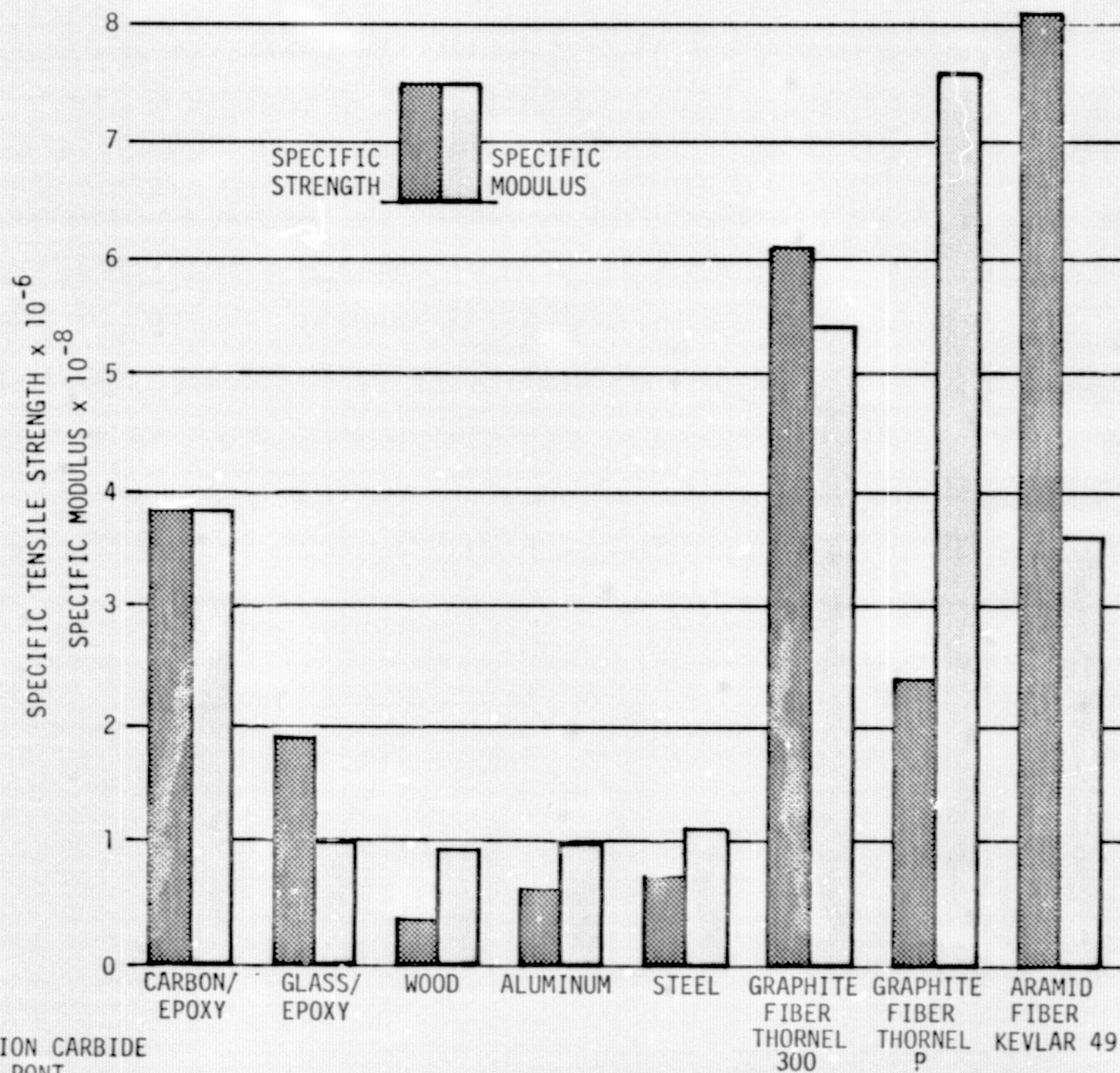
COMPARISON OF SPECIFIC STRENGTH AND MODULI

The composite materials can be most useful in those areas of application where there is a need for weight reduction and simultaneously, a need for preserving the material strength and stiffness.

Specific strengths and specific moduli of materials are expressed as the ratio of tensile strength to density and ratio of tensile modulus to density, respectively.

The chart on the opposite page compares the specific strengths and specific moduli of several graphite fibers, Union Carbide's Thorne1 300 and Thorne1 P, with DuPont's aramid Kevlar 49, and the composite materials using these fibers and epoxy matrix. The specific strengths and moduli of stainless steel, wood and E-glass/epoxy composites are given for comparison

COMPARISON OF SPECIFIC STRENGTH AND MODULI



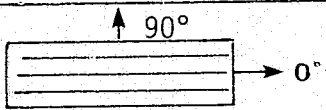
SOURCE: UNION CARBIDE
DU PONT

PROPERTIES OF UNIDIRECTIONAL COMPOSITE MATERIALS

The material properties of advanced composite materials depend on the fiber orientation and the direction of the applied loads. The properties of composites with high structural efficiency (fiber volume in 50 to 60 percent range) and unidirectional alignment of fibers are presented in a tabular form on the opposite page.

If loads are applied along the fiber axis (0°), the properties of composites are determined almost entirely by fiber properties alone. If loads are applied in the transverse direction (90°), however, then the properties of the matrix determine the properties of the composite. Any other direction of load application will result in in-plane or interlaminar shear stresses and failures might occur in those shear modes. The values of in-plane and interlaminar shear strengths are usually quite low. The failure stress in the transverse direction is about 10 percent of the tensile strength along the fibers.

A substantial improvement in strength in transverse direction can be achieved if fibers are aligned in 0° and 90° to applied load. This is, however, accompanied by significant reduction of strength in the direction of applied load.

PROPERTIES OF UNIDIRECTIONAL COMPOSITE MATERIALS						
Fiber Direction 	Graphite/Epoxy			Aramid/ Epoxy Kevlar 49	E-Glass	Steel
	Thorne1 300	Thorne1 P	Magnamite HM			
Tensile Strength 0° (10^3 psi)	182	115	180	200	160	80
Compressive Strength 0° (10^3 psi)	186	130	160	40	85	80
Tensile Strength 90° (10^3 psi)	7.5	N.A.	6	4	5	80
Compressive Strength 90° (10^3 psi)	25	N.A.	20	20	20	80
In-Plane Shear Strength (10^3 psi)	15	12	9	6.4	9	--
Interlaminar Shear Strength (10^3 psi)	N.A.	N.A.	14	8.5	12	--
Modulus of Elasticity 0° (10^6 psi)	17	13	19	11	5.7	28
Modulus of Elasticity 90° (10^6 psi)	N.A.	N.A.	0.9	0.8	1.3	28
Poisson Ratio	0.21	N.A.	0.25	0.34	0.3	0.3
In-Plane Shear Modulus (10^6 psi)	0.65	N.A.	0.7	0.3	0.5	10.6
Sources: DuPont, Union Carbide, Hercules						

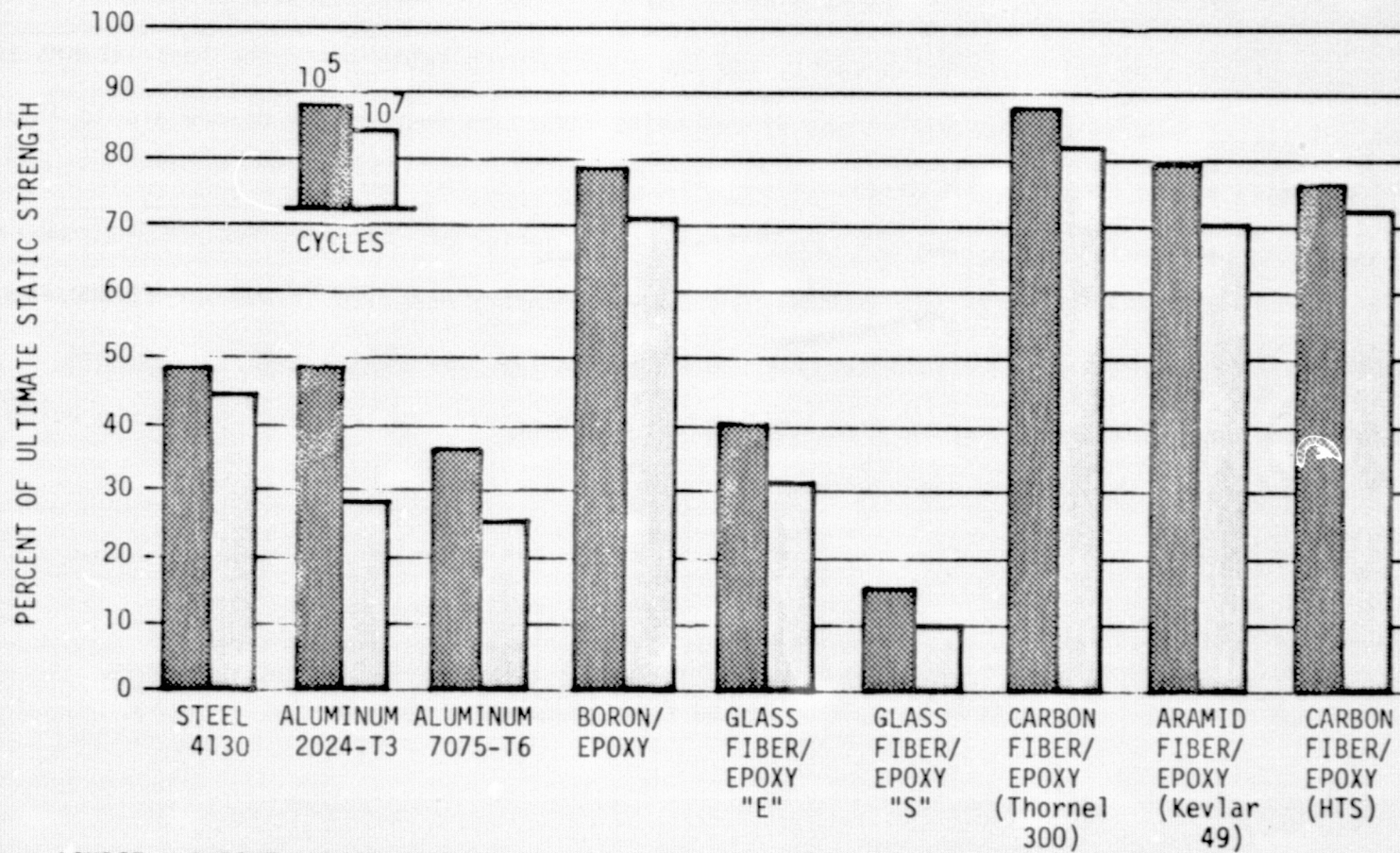
FATIGUE PROPERTIES OF ADVANCED COMPOSITES

The advanced composite materials have excellent fatigue resistance. After 10 cycles of tension-thinner loading in fatigue tests, the ultimate strength of steel is reduced to 50 percent of its static strength. In the case of carbon fibers, this value is in the 80 percent range, and for aramid fibers it is around 70 percent.

These exceptional fatigue properties are attributed to the lack of plastic deformation in the fibers since the comparable materials can stay much longer in the elastic range and thus accommodate much higher stresses.

It should be noted that the fatigue strength is very often the most important criterion used in selecting materials for many engineering applications. Engineers and designers are therefore very interested in the use of composites for the applications requiring a great fatigue resistance.

FATIGUE PROPERTIES OF ADVANCED COMPOSITES



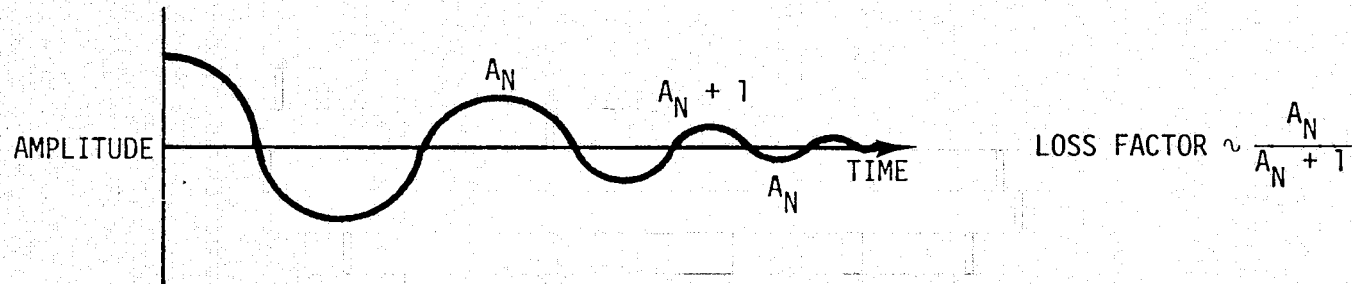
SOURCE: DuPONT, UNION CARBIDE

VIBRATIONAL DAMPING OF ADVANCED COMPOSITE MATERIALS

The very high vibrational damping is another of the outstanding characteristics of advanced composite materials. Vibrational damping could be measured by the decay of free vibrations. The chart on the facing page illustrates this material property and the accompanying table lists the loss factors for various materials. The decay of free vibrations of composite materials (especially of the aramid fibers composite) are much higher than that of steel.

The composites' vibrational damping can be utilized in the design of the drive train (drive shaft) and results in the reduction of noise and vibration, and the secondary benefits of smaller flywheels and other parts of the drive train. Graphite fibers also have a low transmissibility which, when compared with the low vibrational damping characteristics, which results in graphite components being excellent sound deadening and sound reducing material.

VIBRATIONAL DAMPING OF ADVANCED COMPOSITE MATERIALS



DECAY OF FREE VIBRATIONS

<u>MATERIAL</u>	<u>LOSS FACTOR $\times 10^{-4}$</u>
1020 STEEL	<20
DUCTILE CAST IRON	30
GRAPHITE/EPOXY	30
FIBERGLASS/EPOXY	47
KEVLAR 49/EPOXY	160
CURED POLYESTER EPOXY	400

SOURCE: DU PONT

OTHER MECHANICAL PROPERTIES OF ADVANCE COMPOSITES

There are other important mechanical properties of advanced composite materials. Graphite has a very low friction coefficient and good wear resistance. Because of the fiber lubricity, the coefficient of friction of steel on unlubricated graphite/epoxy composites is lower than that of lubricated steel on steel. This property of composites can be successfully utilized in areas where lubrication loss may occur: in antifriction bearings or in the design of brake linings.

The resistance for crack propagation (fracture toughness) in the composite materials is much lower than that in plain carbon steel. If, however, a metal structure is designed to the same strength and modulus, then the fracture toughness of both metal and composite material are about equal. The fracture toughness is poor in the fiber direction since the cracks usually propagate through the resin or fiber/resin interface. A careful design effort has to be made in order to minimize the shear stresses in the direction of fibers.

Graphite fibers exhibit excellent resistance to creep; resins, however, do not. As a result of the composites diverse material properties, the fiber orientation is very important in determining the creep behavior of the material. When load is applied in the fiber direction, the total creep strain is very small compared to instantaneous strain, and a negligible permanent strain remains after unloading.

Impact strength criterion is very important for the automobile application. The tolerance to damages by impact is very good for both graphite and aramid reinforced composites. They do not shatter on impact (as fiberglass does), but only delaminate and still can keep their structural function. Metals absorb the impact energy by their strain energy capacity and plastic deformation. Composites on the other hand, have a different energy absorption mechanism which consists of strain energy capacity, followed by delamination, fiber debonding or fiber pullout.

OTHER MECHANICAL PROPERTIES OF ADVANCED COMPOSITES

- LOW FRICTION COEFFICIENT AND WEAR RESISTANCE OF CARBON FIBERS
 - GRAPHITE FORM OF CARBON = NATURAL DRY LUBRICANT
- RESISTANCE TO CREEP
 - TOTAL CREEP STRAIN VERY LOW AFTER LOAD APPLICATION IN THE FIBER DIRECTION
 - NEGLIGIBLE PERMANENT STRAIN AFTER UNLOADING
- IMPACT RESISTANCE
 - LOWER THAN THAT OF PLAIN STEEL AND HIGHER THAN THAT OF GLASS REINFORCED COMPOSITES
 - NONSHATTERING ON IMPACT
 - ENERGY ABSORPTION BY STRAIN ENERGY, CRACK PROPAGATION, FIBER PULLOUT, DEBONDING AND DELAMINATION
 - ARAMIDS HAVE THE HIGHEST IMPACT STRENGTH. THIS LEADS TO THE POTENTIAL APPLICATIONS OF HYBRID (ARAMIDS/GRAPHITE/EPOXY) COMPOSITES
- FRACTURE TOUGHNESS (RESISTANCE TO CRACK PROPAGATION)
 - LOWER THAN THAT OF PLAIN CARBON STEEL
 - POOR IN FIBER DIRECTION SINCE CRACK PROPAGATES THROUGH THE RESIN OR ALONG THE FIBER/RESIN INTERFACE
 - ARAMID FIBER REINFORCED COMPOSITE INHIBITS CRACK PROPAGATION

Values of the coefficient of thermal expansion along the fibers of graphite/polymer composites are slightly negative, across the fiber they are positive. A typical range of thermal expansion for the fibers is given on the opposite page. A designer can fully utilize this property and adjust the thermal coefficient over a range from -1.3×10^6 to 15×10^6 in/in/°F. In quasi-isotropic laminates, the coefficient of thermal expansion is near zero.

The thermal conductivity is high along the fibers and low in the transverse direction. As a result, the composite material has the ability to dissipate heat which contributes to the high fatigue resistance.

Graphite fibers are electrically conductive and resins are resistant to electrical conductivity. The electrical properties of graphite/resin composite are therefore influenced by fiber volume, fiber orientation, void content and moisture adsorption. Electrical conductivity is exploited when the molded composite surfaces can be electrostatically painted.

One of the most important properties of the graphite composites is their environmental and chemical stability. This property seems especially important if viewed in the light of the importance of the durability and corrosion resistance for automotive vehicles. Fiberglass composites have been successfully used in the chemical and marine industries as well as in some automobiles (i.e., Corvette). The mechanical properties of composites are not significantly affected by degradation of resins on the surfaces. If, however, the load-carrying fibers are simultaneously fractured, then crack propagation and further deterioration of mechanical properties could follow.

The flammability and toxicity of the graphite composite materials, especially those of resins, must be thoroughly examined in relation to fire safety.

THERMAL, ELECTRICAL AND ENVIRONMENTAL PROPERTIES OF ADVANCED COMPOSITES

THERMAL PROPERTIES

- GOOD THERMAL STABILITY
 - COEFFICIENT OF THERMAL EXPANSION RANGE
 - FROM -0.02×10^{-6} to -0.05×10^{-6} IN/IN/°F ALONG THE FIBERS
 - FROM 11×10^{-6} to 20×10^{-6} IN/IN/°F ACROSS THE FIBERS
 - QUASI-ISOTROPIC LAMINATES HAVE NEAR ZERO THERMAL EXPANSION COEFFICIENTS
- THERMAL CONDUCTIVITY
 - HIGH ALONG THE FIBERS
 - LOW ACROSS THE FIBERS

ELECTRICAL PROPERTIES

- FIBER ELECTRICALLY CONDUCTIVE
- POLYMER MATRIX RESISTANT TO ELECTRIC CONDUCTIVITY

ENVIRONMENTAL PROPERTIES

- GOOD ENVIRONMENTAL STABILITY - SURFACE DEGRADATION OF RESIN HAS NO EFFECT ON THE MECHANICAL PROPERTIES UNLESS THE LOAD-CARRYING FIBERS ARE FRACTURED
- GOOD CHEMICAL STABILITY

APPENDIX B

ESTIMATION OF USE OF COMPOSITES IN POST-1985 AUTOMOBILES

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ESTIMATION OF USE OF COMPOSITES IN POST-1985 AUTOMOBILES

Methodology

The objective of this estimation is to determine a reasonable upper bound for use of graphite composite materials in typical domestic automobiles built in the post-1985 period. The following assumptions are made:

- A. Between now and 1985 significant downsizing and material substitution using conventional materials (aluminum, plastic, high strength steel) will reduce the weight of a standard sized car from 4,280 pounds to 3,000 pounds [1, 2]. This reduction in weight, coupled with improved engine technology, will approach the goal of 27.5 mpg in 1985.
- B. Given sufficient incentives for further vehicle weight reductions, the auto manufacturers would first substitute graphite composites for remaining steel structural members where feasible. No substitution for aluminum or plastic is assumed, nor are subsystems that are redesigned to make optimal use of composites considered.
- C. No presumption is made regarding the economic feasibility of the cited graphite composite component substitutions. Selection of composites as candidates for substitution is based only on technical feasibility as indicated by the recent literature.

The calculations are based on the interactive weight reduction model presented in [1]. In this model the vehicle is divided into upper body, lower body and chassis groups; as weight is removed from the upper and lower body groups, structural and power train requirements are reduced, thus propagating weight savings down through the vehicle.

The interaction is illustrated by the following example. The power plant considered in [1] has a weight (in steel and iron) of 793 pounds. Reductions in body weight reduce power requirements so that

the power plant weight is reduced by 166 pounds. Substitution of aluminum for iron in manifolds, head, crankcase and water pump housing [3] would reduce the weight further by 151 pounds. Finally the reduced power plant weight leads to chassis weight reductions of 15 pounds, leaving a new power plant weight of 461 pounds.

Weight Estimates

The weight estimates for post-1985 autos, given the above assumptions, are listed in Table 1. In structural elements, it is assumed that composites will be used as reinforcing in a hybrid structure with steel, thus saving weight while preserving body integrity especially in collisions. From [4, 7], a 35 percent weight saving is achieved through substitution of 40 percent of the steel by 5 percent graphite composites (percents based on original weight).

Composite parts such as suspension elements are complete replacements for steel, with weight savings of 75 percent [5]. Weight savings in door subassemblies are estimated from [6].

Discussion

The 91 pound estimate of graphite composite substitution is lower than previous estimates in the 300 to 400 pound range since these earlier predictions did not consider the effects of downsizing, conventional materials substitution and weight system interactions. It is anticipated that once the auto manufacturers invest in tooling and development to use plastics by 1985, they will continue their use until they amortize the massive capital costs. Therefore, little incentive will exist for the incremental reductions possible from these materials to composites. In contrast, where high specific strength or stiffness is required, composites may provide an excellent substitute for remaining steel components.

No analysis has been performed of the net economic benefit of the use of composites in these parts. Should other fuel-saving technologies prove more cost-effective, less use of composites may result. Therefore, the 91 pound estimate may be considered an upper bound estimate for the substitution of composite materials for iron and steel. On the other hand, more extensive use of composites could result if the automobile manufacturers were to begin with a "clean sheet of paper" and completely redesign vehicles for the use of composites.

Table 1 Estimates of Component Weights (in pounds) Resulting from Materials Substitution

Component Area	Original Weight	New Weight				
		Steel & Iron	Aluminum	Plastics	Other Non-Metals	Graphite Composites
Upper Body:						
Structural Elements	596	358	-	-	-	30
Hood and Deck	160	-	81	-	-	-
Door	170	97	13	7	16	7
Glass	110	-	-	-	93	-
Trim and Seats	279	-	-	120	120	-
Lower Body:						
Rails and Sills	321	173	-	-	-	14
Chassis:						
Power Plant	793	324	137	-	-	-
Final Drive	188	73	15	-	-	7
Forestructure	181	65	-	-	-	5
Suspension, Steering, Brakes	523	177	-	-	-	24
Wheels and Tires	244	-	-	35	104	-
Exhaust and Fuel System	79	50	-	-	-	-
Bumpers	177	50	-	-	-	4
Subtotals	3,821	1,367	246	162	333	91
TOTALS	3,821			2,199		

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